Design And Fabrication Of Space Variant Micro Optical Elements

Pradeep Srinivasan
University of Central Florida
DESIGN AND FABRICATION OF SPACE VARIANT MICRO OPTICAL ELEMENTS

by

PRADEEP SRINIVASAN
B.E. Electrical Engineering, University of Madras, 2000
M.S. Electronic Materials and Devices, University of Cincinnati 2003

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Major Professors: Eric G. Johnson & Patrick L. LiKamWa
ABSTRACT

A wide range of applications currently utilize conventional optical elements to individually transform the phase, polarization, and spectral transmission/reflection of the incident radiation to realize the desired system level function. The material properties and the feasibility of fabrication primarily impact the device and system functionality that can be realized. With the advancement in micro/nano patterning, growth, deposition and etching technology, devices with novel and multiplexed optical functionalities have become feasible. As a result, it has become possible to engineer the device response in the near and far field by controlling the phase, polarization or spectral response at the micro scale. One of the methods that have been explored to realize unique optical functionalities is by varying the structural properties of the device as a function of spatial location at the sub-micron scale across the device aperture. Spatially varying the structural parameters of these devices is analogous to local modifications of the material properties.

In this dissertation, the optical response of interference transmission filters, guided mode resonance reflection filters, and diffraction gratings operated in Littrow condition with strategically introduced spatial variation have been investigated. Spatial variations in optical interference filters were used to demonstrate wavelength tunable spatial filters. The effect was realized by integrating diffractive and continuous phase functions on the defect layer of a one-dimensional photonic crystal structure. Guided mode resonance filters are free space optical filters that provide narrow spectral reflection by combining grating and waveguide dispersion effects. Frequency dependent spatial reflection profiles were achieved by spatially varying the grating fill fraction in designed contours. Diffraction gratings with space variant fill fractions operating in Littrow condition were used to provide graded feedback profiles to improve the
beam quality and spatial brightness of broad area diode lasers. The fabrication of space variant structures is challenging and has been accomplished primarily by techniques such as ruling, electron beam writing or complex deposition methods. In order to vary the desired structural parameter in a designed manner, a novel technique for the fabrication of space variant structures using projection lithography with a fidelity that rivals any of the current technologies was also developed as a part of this work. The devices exhibit wavelength dependent beam shaping properties in addition to spatial and spectral filtering and have potential applications in advanced imaging systems, graded reflectivity laser mirrors, and engineered illumination. The design, modeling, microfabrication and experimental characterization of space variant micro optical elements with novel optical functionalities are presented.
“Apurvha kopi koshoyam vidyate tava Bharati;
Vyayato vrudhim aAyAti kshayam aAyati sanchayat.”

"Knowledge is unique among all treasures;
It grows when it is spent and it is lost when accumulated and unused.

– Sanskrit verse
To my family, friends and coworkers who have provided me with support and inspiration throughout this journey
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TABLE OF CONTENTS

LIST OF FIGURES .......................................................................................................................... x
LIST OF TABLES ............................................................................................................................ xx

1 INTRODUCTION .......................................................................................................................... 1
  1.1 Diffraction Gratings ............................................................................................................ 3
  1.2 Phase Control ................................................................................................................ 7
  1.3 Narrow-band Spectral Reflection Filters ...................................................................... 12
  1.4 Narrow-band Spectral Transmission Filters ..................................................................... 17
  1.5 Polarization Filters ......................................................................................................... 21
  1.6 Research Overview ......................................................................................................... 23
  1.7 Dissertation Outline ....................................................................................................... 26

2 MICRO OPTICS FABRICATION ................................................................................................. 28
  2.1 Gratings ........................................................................................................................ 29
    2.1.1 Ruling of Gratings ................................................................................................. 29
    2.1.2 Holographic Lithography ..................................................................................... 31
    2.1.3 E-beam and Optical Lithography .......................................................................... 32
  2.2 Diffractive and Refractive Optics using Optical Lithography ........................................ 35
    2.2.1 $2^N$ Patterning and Additive lithography ............................................................ 35
    2.2.2 Additive Lithography ........................................................................................... 35
    2.2.3 Analog Optics Technologies ................................................................................. 37
  2.3 Transfer Etching ............................................................................................................. 38
  2.4 Summary ....................................................................................................................... 39

3 SPACE VARIANT STRUCTURES USING PROJECTION LITHOGRAPHY ....................... 41
  3.1 Description of the Concept ............................................................................................. 44
  3.2 Exposure Model ............................................................................................................. 47
  3.3 Fabrication Process Flow ............................................................................................... 49
  3.4 Results and Discussion ................................................................................................. 50
  3.5 Sub-Resolution Patterning on the GCA Stepper ............................................................ 56
  3.6 Summary ....................................................................................................................... 57

4 MICRO OPTICAL SPATIAL AND SPECTRAL FILTERS ...................................................... 59
  4.1 Introduction .................................................................................................................... 59
  4.2 Numerical Analysis ....................................................................................................... 65
LIST OF FIGURES

Figure 1.1: Sub wavelength grating structure behaves as a homogenous layer with effective index dependent upon the period to wavelength ratio and fill fraction .................................................... 4

Figure 1.2: Tapered sub-wavelength structures for improved anti reflection behavior.......... 8

Figure 1.3: Different schemes of fill fraction variation found in literature ......................... 9

Figure 1.4: Grating structures with different duty cycles are shown in figure. The effective refractive index is fill fraction dependent and tends towards the lower refractive index material for decreasing fill fractions. The limiting value occurs when the wavelength is a lot larger compared to the grating period. .................................................................................................... 10

Figure 1.5: (a) Refractive index variation with respect to grating fill fraction and definition of the parameters used in the equations and (b) Prediction of broadband behavior of artificial coded optical diffractive elements................................................................. 11

Figure 1.6: Dependence of fractional reflection and line width upon layer index contrast. (a) The linewidth for a large refractive index contrast is on the order of 100nm for a small number of layers. (b) The fractional power reflected from the structure approaches unity even for 8 periods as the refractive index contrast is increased. (c) To obtain a filter with narrow linewidth, the index difference between the component layers is chosen to be small. (d) A large number of layers are required to obtain the a fractional power reflection close to 1. ........................................ 12

Figure 1.7: (a) Unit cell of the layered structure with a 1.0µm period grating etched. (b) Calculated reflection response from the structure as a function of fill fraction. The spectral reflection band becomes narrower and the peak reflection drops for decreasing fill fraction due to the lower index contrast........................................ 15
Figure 1.8: (a) The schematic, operating principle and device design of a guided mode resonance filter (GMR). (b) Spectral reflection obtained from a guided mode resonance filter

Figure 1.9: Photonic crystal structure with a defect layer produces a narrow transmission within a wide stop band.

Figure 1.10: (a) Comparison of the transmission linewidth and stop band for a filter composed of 4 and 6 SiO/SiN pairs on either side of the spacer layer. (b) Transmission through a filter composed of 5 pairs of a-Si/SiO layers on either side of the defect layer.

Figure 1.11: Schematic diagram of an image array integrated with space variant filters that transmit different wavelengths [36]

Figure 1.12: Unit structure of a space variant transmission filter generated by spacer layer thickness modulation [37]

Figure 1.13: Simulated performed of broadband dual layer wire grid polarizer [38]

Figure 1.14: Polarization converting elements fabricated by Autocloning techniques [41]

Figure 1.15: Proposed optical components. (a) 3D space variant Filter Elements with Engineered Defects to control the spatial and spectral transmission profile; (b) Space variant gratings that provide variable reflectivity for improvement of beam quality of broad stripe laser diodes; (c) Space variant guided mode resonance filter that provides wavelength dependent spatial reflection profiles

Figure 2.1: Picture of a ruling engine

Figure 2.2: (a) Schematic of a holographic exposure system and (b) Dependence of exposed period on angle of interfering beams

Figure 2.3: Schematic diagrams of electron beam and (g-line) projection lithography system

Figure 2.4: Schematic representation of a 2N technique for the fabrication of diffractive optics
Figure 2.5: Additive lithography process using entire domain masking.

Figure 2.6: Duty cycle dependence of 0th order diffraction efficiency of a phase grating [48]...

Figure 3.1: The response curve for a 1 µm thick Shipley1813 photoresist coating is shown. The grating was exposed (tgrating) by delivering less than 90% of the saturation dose (tclear). The analog intensity function was then overlaid with an exposure dose (tov) value less than the estimated threshold dose (tth) such that it will not further expose the resist line areas.

Figure 3.2: (a) The grating aerial image intensity profile due to the first exposure using the grating amplitude mask is shown. (b) The overlaid analog aerial image intensity profile, from the second exposure and (c) The combination of exposures (a) and (b), results in separating the grating structure in a region with a “nominal” analog bias to the left, and a region with a “high” analog bias to the right of the graphic shown. In the “high” intensity region, the grating grooves develop thinner than the ones at the “nominal” exposure region. For clarity 10 µm of the spatial extent is shown in all images.

Figure 3.3: By using the threshold region to control the combined exposure (tgrating + tov), the line width can be varied over a large range (red lines). In the case that the overlay exposure is greater than estimated threshold (tov > tth), the patterns are washed-out after development, since the entire exposure profile is shifted to values above the exposure threshold (blue line).

Figure 3.4: (a) Feature Size variation as a function of exposure dose: experimental and predicted values for process parameter $\gamma = 0.6$ and, (b) predicted dose variation as a function of the grating period, based on the same simulation model.

Figure 3.5: (a, b) Comparison of numerical and experimental results for the duty cycle variation obtained with a one dimensional grating exposure overlaid with an analog intensity function; (c, d) SEM images of the variable fill fraction gratings (e, f) Magnified images of the transition from
the phase mask controlled analog intensity region to the open aperture in the low and high fill-
fraction regions. ............................................................................................................................ 53

Figure 3.6: The effect of an analog exposure ‘ramp’ profile overlaid on a 2-D grating. (a) As the
overlay dose increases, the adjacent holes overlap and the structure transitions from a hole-array
to a post-array. (b) Magnified micrographs of the photoresist, taken at a 30° tilt, showing the
sidewall and cleared photo resist at different spatial coordinates in the patterns shown in (a). The
profile of the structures is slightly conical, with a larger opening on the air side. This is attributed
to resist loss during development .................................................................................................. 54

Figure 3.7: Quantitative results from the exposures of the 2-D grating of Figure 6. The duty cycle
variation range was adjusted by varying the analog exposure dose (tov). The resulting fill-
fraction of the grating varied from (a) 0.53 - 0.7 and from (b) 0.6 - 0.8 in the micrographs. ..... 55

Figure 3.8: 1 µm period grating structures obtained on the GCA g-line stepper by double
patterning a 2 µm period grating in 1µm thick photoresist ............................................................................................................................. 57

Figure 4.1: (a) Annular pupil filter array used to enhance the resolving power of a Shack-
Hartmann wavelength sensor (b) Different polarization matched orientations of a wedge spatial
filter used to improve the patterning fidelity in a high numerical aperture lithographic projection
imaging system ............................................................................................................................. 59

Figure 4.2: Cross section of DBR spectral filter ........................................................................... 61

Figure 4.3: Schematic diagram of the proposed filter elements with engineered defect layers for
spatial and spectral control of transmission .................................................................................. 63

Figure 4.4: Refractive index of the PECVD grown SiO film and SiN films for the (a) and (b)
1.55 µm regime and (c) and (d) for the 3-5 µm regime ................................................................ 66
Figure 4.5: (a&c) Transmission through the SiO/SiN device as a function of defect layer thickness. (b&d) Transmission spectra through the same device for five defect layer thicknesses.

Figure 4.6: Schematic of the space variant transmission filter fabrication by defect layer thickness modulation.

Figure 4.7: Etching selectivity of silicon oxide in a CHF3/O2 plasma as a function of percentage of oxygen in the chemistry. The curves were generated empirically on a Unaxis Versaline oxide etcher using an ICP power of 600 W and an RIE power of 80W at an operating pressure of 10mTorr.

Figure 4.8: (Left) Illustration of 3×3 pixel arrays with RMS roughness (Right) Microscope image of a 3×3 pixel array.

Figure 4.9: Microscope images of micro-optical structures.

Figure 4.10: Illustration and microscope image of an 8-level, charge 2, vortex lens.

Figure 4.11: Sample wafer layout and summary of defect thicknesses.

Figure 4.12: Interpretation of experimental results.

Figure 4.13: FTIR transmission data of 4×4 pixel array showing strong tuning response.

Figure 4.14: (a) Micrograph of the charge 2 vortex elements. (b) Simulated (dotted lines) and experimental transmission spectra.

Figure 4.15: Images of the transmission through the vortex element at different transmission wavelengths. The vortex element was illuminated using a beam of diameter 3-mm.

Figure 4.16: (a) The graph shows transmission as function of defect thickness for a constant wavelength used to determine the aperture size. (b) Annular rings of transmission observed by illuminating analog elements.
Figure 4.17: Analytically estimated diffraction spot dimensions (a) A lateral spot size of 6 µm was estimated at a wavelength of 1548 nm and (b) An axial spot size of 100 µm was estimated.

Figure 4.18: Experimentally diffracted spot had a full width at half max of 17 µm. The discrepancy in the lateral spot size from the estimated value of 6 µm was attributed to the 9 µm pixel size of the imaging camera that was used in the measurement.

Figure 5.1: Gain and loss mechanisms in a semiconductor laser diode. The role of the spectral mirror is to provide preferential reflectivity to the desired axial modes.

Figure 5.2: Schematic illustration of the dual grating reflector concept.

Figure 5.3: Schematic illustration of the spatial beam profile from a broad are Fabry Perot laser.

Figure 5.4: Schematic representation of multifunctional grating out couplers implemented in grating coupled surface emitting laser devices to achieve focusing, collimation or splitting of the beam.

Figure 5.5: Graded reflectivity littrow gratings were used to lock broad area diode lasers to achieve spatial brightness enhancement. The graded reflection was generated by varying the grating depth spatially. (b) Different configuration for spatial beam.

Figure 5.6: Coupled cavity laser with phase conjugate section using aspheric mirrors for lateral lasing mode shaping. Adapted from Z. H. Yang and J. R. Leger, 2004 [96]

Figure 5.7: (a) Schematic diagram of the proposed compact broad area laser (BAL) device with externally mounted grating operated in Littrow condition (b) Schematic diagram of the proposed broad area laser (BAL) with externally mounted space variant grating operated in Littrow condition.
Figure 5.8: The grating coupled surface emitting laser (GCSEL) is well suited for our application. The loss in effective reflection from the external mirror due to the graded reflectivity does not result in significant drop in the output efficiency of the diode laser. ........................................... 96

Figure 5.9: (a) The reflectivity as a function of grating depth for a 50% duty cycle and different grating periods is shown. (b) The reflectivity as a function of fill fraction for an etch depth of 1.6µm for different grating periods is shown. .............................................................................. 99

Figure 5.10: Plot of grating fill fraction required to achieve the required reflectivity variation. 101

Figure 5.11: SEM images of a coating of Ti/Au on a silicon grating. Uniform coating of gold was achieved on the grating. The ridges seem on the grating sidewalls are a result of the pulsed etching of the BOSCH process ................................................................................................... 102

Figure 5.12: (a) Top view of the fabricated variable fill fraction gratings. An analog intensity profile that generates a pair of cylindrical lenses was used. (Inset) Magnified images of the the grating at different spatial locations. The rectangles indicate the region which has been magnified. (b) The plot of fill fraction variation from the edge to the center of the variable duty cycle grating structures. The minimum grating duty cycle was 0.24 and the maximum was 0.3. (c) Simulated plot of reflectivity variation as a function fill fraction for a grating period of 1.35µm and etch depth of 1.6 µm. For the fabricated structures, the reflectivity varies between 92.48% at the center of the laser stripe which is 200 µm wide down to 73 % at the edge of the beam that interacts with the littrow gratings............................................................................... 104

Figure 5.13: (a) Experimentally measured lasing spectra for locking using straight stripe gratings are shown. The stabilization wavelengths were 966.2nm, 974nm and 979.5 nm for feedback grating periods of 1.42 µm, 1.32 µm and 1.25 µm. (b) The output power as a function of pump
current for pulse operation was measured to be 0.82 W/A which was comparable to the GCSEL devices with integrated dual grating reflectors. ................................................................. 105

Figure 5.14: Efficiency, spectral linewidth and Beam Profile of the broad stripe diode lasers locked using external gratings in Littrow condition. (a) Comparison of the efficiency measured using uniform and space variant external gratings. (b) The spectral linewidth was 0.25nm and was comparable to those achieved from the integrated DGR devices. Devices locked using space variant and uniform gratings at a pumping condition of (c) 5A and (d) 8A. The repetition rate was 10 KHz for each................................................................................................................... 107

Figure 6.1: A space variant GMR filter for beam shaping. Different wavelengths incident on the filter will have different beam shapes that vary with wavelength.............................................. 111

Figure 6.2: (a) Schematic of a Guided Mode Resonance Filter (b) Spectral Reflection as a function of hole diameter in the grating region (lighter regions represent higher reflection) .... 112

Figure 6.3: Comparison of the analytical and simulated curves for power reflection as a function of feature size or fill fraction ...................................................................................................... 114

Figure 6.4: Comparison of the reflection profiles for a FMHM of (a) 20 nm and (b) 50 nm. For the reflection profile to exhibit no strong spatial nulls and provide a uniform reflectivity variation, the fill fraction variation that was fabricated on the wafer was kept within the full width half max of the power reflection vs. feature size curve. ................................................................. 115

Figure 6.5: Analytical transmission profiles for (a) & (c) linear and (b) & (d) quadratic spatial variation of feature sizes. Analytical transmission profiles for (a) & (b) an ideal GMR with 100 % peak reflection and (c) & (d) ‘real’ GMR of finite size..................................................... 116

Figure 6.6: (a) The reflection profile as a function of feature size for different illumination wavelengths. (b) The simulated spectral reflection from the guided mode resonance filters with
variable fill fractions is shown. The spectral reflection from the element is expected to have a wider linewidth due to the multiple fill fractions illuminated by the beam.

Figure 6.7: (a) Aerial image intensity at the wafer plane of a lithographic stepper tool from a hexagonal grating cell when ‘added’ in resist to (b) the aerial image intensity from a phase only mask results in (c) a grating with space variant fill fraction. The local fill fraction is a function of the local dose. The fill fraction at the center of the unit space variant grating cell is the largest and decreases radially in concentric circles across the element. In the aerial intensity images, the lighter regions represent higher intensity.

Figure 6.8: (a) Patterned feature size variation as a function of deviation from the optimal dose. The optimal dose is the dose required to size the features according to the mask design.

Figure 6.9: (a) SEM image of the fabricated grating on the guided mode filter element. (b) Corresponding measured spectral reflection from the device.

Figure 6.10: (a) Fill Fraction variation as a function of spatial location. (b) Spectral measurement on the filters with fill fraction variation.

Figure 6.11: (a) Simulated spatial reflectivity as a function of wavelength and (b) corresponding transmission profiles for a Gaussian input beam.

Figure 6.12: Experimentally measured transmission profiles. (a) Input Gaussian beam, (b) Flat top profile below resonance (c) Central null in transmission at resonance and (d) Reduced diameter Gaussian beam is obtained above the measured spectral resonance.

Figure 6.13: (a) The Gaussian beam after propagation illuminates more than one lens in the array. (b) As a result, the reflection profile encountered by the beam at the GMR was modified.
Figure 6.14: (a) Simulated profile of the reflected beam close to the space variant GMR mirror at resonant illumination (b) Simulated beam profile at the detector plane after propagation of 6.2 cm at resonant illumination.............................................................. 129

Figure 6.15: Measured beam profiles when the illumination wavelength was (a) at resonance and (b) above resonance. .............................................................. 129
LIST OF TABLES

Table 1-1: Types, functionality, fabrication technique and applications of space variant structures .............................................................. 6

Table 3-1: Comparison of techniques for Space Variant Grating Fabrication ........................................ 42

Table 4-1: Measured level heights of the fabricated diffractive vortex element ............................. 76

Table 5-1: Grating Specifications ............................................................................................... 100
1 INTRODUCTION

Conventional optical elements use surface relief to transform the incident radiation to realize the desired device level functionality. They typically impact a single property of the incident radiation such as phase, polarization, spectral or spatial transmission/reflection. The materials out of which they are constructed are chosen to provide maximum flexibility during the design process as well to facilitate ease of fabrication. Lenses, prisms, gratings and other useful optical devices have been well researched and analyzed and have been used to facilitate higher level optical system level functionality. Different wavelength dependent material properties such as refractive index, absorption, birefringence, and other important properties have been characterized for a variety of different dielectrics, metals, semiconductors and more recently polymers. Typically, these optics are constructed at the macro scale and rely on sophisticated opto-mechanical alignments for systems level integration.

The proliferation of communications technology has driven the requirements for miniaturized optics for effective beam manipulation at the mini/micro scale. It became apparent that beam modifications and shaping at the micro scale had important advantages since methods of assembling pre-aligned micro optical elements led to the development of integrated optics that has revolutionized optical systems. Conventional micro and diffractive optics consists of surface-relief structures designed using scalar methods [1]. These micro/nano optical elements can be categorized into refractives, diffractives, multilayer dichroics, photonic crystal structures and polarization gratings. The fabrication technologies for constructing optical elements at the micro-scale were primarily borrowed from concepts developed for integrated circuit fabrication though multiple unique enhancements have also been developed. Passive optical components such as lenses [2, 3], prisms [4, 5], and mirrors [6] have been realized using wafer based
fabrication techniques such as microlithography and transfer etching. These devices have found a host of applications in imaging [7, 8], adaptive optics [9], sensors [10, 11], microscopy [12, 13], communications [14, 15], micro-fabrication [16, 17], beam shaping [18, 19], and more. Material properties, however, remain a fundamental limitation.

With the growth in enabling technologies to construct nano-structured materials, it has now become possible to create artificial materials or meta-materials with structure dependent optical properties [20-23]. These include the use of structured dielectric operating primarily in the sub-wavelength regime to provide artificial refractive index, polarization response or spectral characteristics, use of photonic crystals for dispersion engineering [24-26] and use of metal-dielectric structures for the realization of negative refraction and left handed materials. They are constructed at a scale that is comparable to the operating wavelength and have optical properties that differ significantly from their bulkier macroscopic counterparts. The optical functionality is tailored by custom engineering the structural parameters of the components to achieve the desired material properties. Spatially varying the structural parameters is analogous to modifications in the material properties. A number of novel optical components such as broadband diffractives, polarization converting elements, advanced polarization sensors and broadband antireflection elements have been realized using space-variant micro structures. Central to all of these approaches is the use of 2D or 3D micro and nano-structuring to achieve unique optical effects and properties.

In this thesis, we have further developed and applied the concepts of space-variant micro and nano structuring to create elements with unique multiplexed spatial and spectral functionality. This was achieved by strategically introducing spatial variations in the structural parameters of micro structured spectral filter elements. This concept was investigated in optical filters that
operate using different optical phenomena. The properties of the device were comprehensively studied to analyze the response as a function of each structural parameter using analytical and numerical modeling. The structural parameter was chosen with a view to achieve controlled modification of the desired optical functionality with maximum effect. The ability to reliably introduce the desired variations in the fabrication step was considered rigorously in the design procedure. In this dissertation, the optical response of space variant interference transmission filters, guided mode resonance reflection filters, and diffraction gratings operated in Littrow condition were investigated. Continuous and discrete phase elements were introduced as the defect in multilayer thin film interference filters to obtain novel devices with wavelength dependent tuning of the spatial transmission and reflection. The duty cycle of a guided mode resonance filter was spatially modulated to achieve, for the first time, frequency dependent continuously graded spatial reflection and transmission profiles. The fill fraction of a linear grating operated in Littrow condition was varied spatially to obtain brightness enhancement of broad area laser devices. A novel method to fabricate space variant gratings was demonstrated, for the first time, using projection lithography on a stepper tool. This allows the reliable fabrication of designed space variant structures and rivals the fidelity of existing techniques. The rest of this chapter introduces and outlines different classes of micro optical elements – gratings, spectral and polarization filters – and their applications to space variant optical elements.

1.1 Diffraction Gratings

Diffraction gratings are a cornerstone of modern optics and science in general. They perform a simple yet fundamentally important transformation on the incident radiation. The diffraction grating disperses the radiation into wavelength dependent angular directions. The location of
these spectral orders and their spatial frequency can be described using the scalar diffraction grating equation.

\[ n_i \sin \theta_i + n_r \sin \theta_r = \frac{m \lambda}{d}; \quad m \in 0,1,2,3\ldots \]  \hspace{1cm} (1.1)

The angular dispersion is dependent upon the refractive indices of the media on incidence and diffraction regions \( (n_i \text{ and } n_r) \) respectively, the grating period \( (d) \) and wavelength \( (\lambda) \). A grating can be amplitude or phase grating operating in transmission or reflection. Under plane wave illumination, the diffraction grating can also be considered to perform a Fourier transform of the radiation incident on it. As the period of the grating gets smaller, the angular location of the higher diffracted orders with respect to the incidence angle becomes larger. In the limiting condition when the grating period is smaller than the wavelength of the incident radiation, all diffracted orders become evanescent.

\[ \perp \quad \mathcal{E} \quad \parallel \]

Figure 1.1: Sub wavelength grating structure behaves as a homogenous layer with effective index dependent upon the period to wavelength ratio and fill fraction

4
In these conditions the scalar theory breaks down and other rigorous forms of grating analysis are necessary to accurately predict performance. At the sub wavelength scale, the grating structures behave as a layer with effective index dependent upon the period to wavelength ratio and fill fraction. The effective index of such gratings can be estimated analytically using the following equations [22].

\[
\varepsilon_{\perp} = \varepsilon_{0}^{0} \left(1 + \frac{\pi^2}{3} \left(\frac{A}{\lambda}\right)^2 f^2 (1-f)^2 \left(\frac{\varepsilon_s - \varepsilon_o}{\varepsilon_o \varepsilon_{\perp}^0}\right)\right) \\
\varepsilon_{\parallel} = \varepsilon_{0}^{0} \left(1 + \frac{\pi^2}{3} \left(\frac{A}{\lambda}\right)^2 f^2 (1-f)^2 \left(\frac{\varepsilon_s - \varepsilon_o}{\varepsilon_o \varepsilon_{\parallel}^0}\right)\right) \\
\varepsilon_{\perp}^0 = f \varepsilon_s + (1-f) \varepsilon_o \\
\frac{1}{\varepsilon_{\parallel}} = f \frac{\varepsilon_s}{\varepsilon_o} + 1 - f \frac{\varepsilon_s}{\varepsilon_o}
\]

Here, \(A\) is the period of the sub-wavelength grating, \(\lambda\) is the period of the incident wavelength, \(\varepsilon_s\) is the permittivity of the substrate, \(\varepsilon_o\) is the permittivity of free space. The permittivity experienced by the orthogonal parallel and perpendicular to the grating grooves are represented by \(\varepsilon_{\parallel}\) and \(\varepsilon_{\perp}\) respectively. These equations show that a linear sub-wavelength grating functions as a layer with different refractive indices for orthogonal polarization states. Furthermore, the refractive index is also dependent upon the grating fill fraction and the period to wavelength ratio [27]. Thus, the response of the diffraction grating can be manipulated by controlling the parameters of grating such as fill fraction, period, depth and orientation.

Space variant gratings vary the structure dependent properties of the grating locally. They offer the ability to locally affect the phase, spectrum, intensity and polarization of incident radiation. The local transformation of the incident radiation can result in large scale macroscopic
changes in the far field. As a result, they can be used to comprehensively transform the incident radiation and tailor the same to suit the required output characteristics. Several of these properties of space variant structures have been demonstrated using different grating configurations.

Table 1-1: Types, functionality, fabrication technique and applications of space variant structures

<table>
<thead>
<tr>
<th>Space-variant structures</th>
<th>Optical Functionality</th>
<th>Method of Fabrication</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable Fill Fraction</td>
<td>Ability to locally vary the effective index in the case of SW gratings</td>
<td>E-Beam, Exposure through a phase mask</td>
<td>Broadband Diffractives</td>
</tr>
<tr>
<td>Variable Depth</td>
<td>Improvement in side lobe suppression via apodization</td>
<td>Exposure through a phase mask</td>
<td>Apodized DBRs</td>
</tr>
<tr>
<td>Curved Gratings</td>
<td>Ability to create focusing and diverging beams</td>
<td>Scanning methods, micro-molding</td>
<td>Imaging and spectroscopy</td>
</tr>
<tr>
<td>Variable Line Space</td>
<td>Provide local phase control for controlled far field patterns</td>
<td>Ruling Engines, holographic and phase mask exposure</td>
<td>Aberration correction, imaging and Spectroscopy</td>
</tr>
<tr>
<td>Tapered Structures</td>
<td>Provide graded index layers for better impedance matching</td>
<td>Plasma etching processes</td>
<td>Antireflection Structures</td>
</tr>
<tr>
<td>Space Variant Photonic Crystals</td>
<td>Control over reflection and transmission spectra and intensity</td>
<td>Electron beam, holography, micro-molding, self assembly</td>
<td>Filtering and Imaging applications</td>
</tr>
</tbody>
</table>

Table 1-1 summarizes the types of space variant gratings found in literature along with their application and method of fabrication used. The grating fill fraction and depth controls the power intensity distribution in the diffracted orders at the super wavelength scale. The coupling efficiency of the grating structure can be controlled locally by varying these parameters. Variable fill fraction and variable depth gratings are used in apodization applications for improving the side lobe suppression ratios of fiber Bragg gratings and imaging applications. They have also been used for tailoring the spatial beam characteristics of a diode laser in grating
coupled surface emitting laser. Curved gratings are one or two dimensional grating structures that are formed on curved surfaces. The fabrication of curved gratings is typically accomplished using micro molding techniques or scanning methods that can be used to write or curved surfaces. The grating parameters remain constant and a phase that is provided by the surface curvature is added on the transmitted or reflected beam. Variable line space (VLS) structures are typically linear gratings that have a space variant period and orientation. A change in the orientation of a linear grating structure results in a phase change in the spatial frequency domain when the grating period is larger than the period of the radiation incident upon it ($\Lambda > \lambda$). This effect has been exploited for aberration correction in imaging systems. At the sub-wavelength scale, VLS structures have been used for realizing polarization converting elements. Tapered structures offer a variable fill fraction in the direction of light propagation and have been used to improve impedance matching for antireflection applications. A brief overview of the optical properties of each of these grating structures along with their applications will be discussed in the following sections. With advances in microfabrication technology, the use of space variant gratings for the micro scale control of phase, spectrum, polarization and intensity of transmission or reflection to comprehensively manipulate the incident radiation in the near and far field holds promise.

1.2 Phase Control

The dependence of effective refractive index upon grating fill fraction has been exploited for realizing structural anti reflection coatings and broadband diffractive optical elements. Single film antireflection coatings are composed of a film with refractive index $n_{AR} = \sqrt{n_s n_s}$, where $n_{AR}$ is the refractive index of the thin film $n_s$ and $n$ are the substrate and superstrate indices respectively. The layers have a quarter optical wavelength thicknesses. These coatings typically have poor performance at off-design wavelengths and non-normal incidence. Conventionally,
these issues are resolved by using multiple coatings that increase the overall complexity of the coating design. Sub-wavelength gratings with a 0.5 fill fraction and quarter wave thickness were used to realize antireflection structures for high index materials [28]. In order to simulate the use of multiple coatings for improved AR behavior, tapered sub-wavelength gratings with a pyramidal and Klopfenstein taper function were used. These structures provide a graded effective index and result in improved coating properties. These effects were exploited for the realization of broader wavelength response for anti reflection structures (Figure 1.2).

Several schemes of duty cycle variation in the plane of incidence have been proposed in literature. Fill fraction variation parallel and perpendicular to the groove direction for linear gratings have been explored as well as duty cycle variation in two-dimensional grating structures. Some of these schemes are shown in Figure 1.3. The effective index variation as a function of duty cycle has been used in the realization of broadband diffractive optical elements. These elements achieve the desired phase depth using an index modulation rather than a depth modulation as in a conventional surface relief optical structure.

The broadband performance of the diffractive optical structures formed from these media was due to the fact that the grating dispersion of the diffractive optical element (DOE) was
compensated by the dispersion of the sub-wavelength structures that form the DOE. The fill fraction can be varied in a variety of different schemes for one and two-dimensional grating structures. They provide a high diffraction efficiency over a wider wavelength range due to the fact that differential phase accumulated at wavelengths off the design is similar due to the dispersion properties of these structures (Figure 1.4).

![Figure 1.3: Different schemes of fill fraction variation found in literature](image)

The effective index variation with fill fraction for gratings in a square lattice formed in silicon in air are shown in Figure 1.4. The calculation of the diffraction efficiency spectrum is a task that can be attempted only numerically. The analysis of broadband performance was examined analytically in a paper by Sauvan et.al [29]. The relationship between the phase transfer functions $\phi(f, \lambda)$ and $\phi(f, \lambda_0)$ is given by

$$\phi(f, \lambda) = \frac{\lambda_0}{\lambda} \left[ \frac{n(f, \lambda) - n_{\min}(f, \lambda)}{n(f, \lambda_0) - n_{\min}(f, \lambda_0)} \right] \phi(f, \lambda_0)$$

1.6
Under the assumption that the ratio 
\[
\frac{n(f, \lambda) - n_{\text{min}}(f, \lambda)}{n(f, \lambda_0) - n_{\text{min}}(f, \lambda_0)}
\]
depends only weakly on \(f\), and is related to the value for given local fraction of etched material corresponding to, the relationship between \(\phi(f, \lambda)\) and \(\phi(f, \lambda_0)\) becomes

\[
\phi(f, \lambda) = \frac{\lambda_0}{\lambda} \frac{\Delta n(\lambda)}{\Delta n(\lambda_0)} \phi(f, \lambda_0)
\]

Figure 1.4: Grating structures with different duty cycles are shown in figure. The effective refractive index is fill fraction dependent and tends towards the lower refractive index material for decreasing fill fractions. The limiting value occurs when the wavelength is a lot larger compared to the grating period.

The first-order efficiency diffraction efficiency can then be calculated as [29],
\[ \eta(\lambda) = snc^2 \left[ 1 - \frac{\Delta n(\lambda)}{\Delta n(\lambda_0)} \right] \]  

where the function \( snc = \sin(\pi x) / \pi x \). Up to a third-order approximation in \( (\Lambda_s / \lambda)^0 \) the dispersion relation of the artificial material can be written as [30]

\[ n(\lambda) = n_s + n_2 (\Lambda_s / \lambda)^2 + O((\Lambda_s / \lambda)^4) \]

\[ \eta(\lambda) = \sin c^2 \left[ 1 - (1 + \alpha) (\lambda_0 / \lambda) + \alpha (\lambda_0 / \lambda)^2 \right] \]  

(1.10)

where \( \alpha = \left[ \frac{(n_{\min}(\lambda_0) - n_{\min}(\lambda_s)) - (n_{\max}(\lambda_0) - n_{\max}(\lambda_s))}{\Delta n(\lambda_0)} \right] \)

It is well known that the diffraction efficiency of a standard echellette grating is given as,

\[ \eta_e = \sin c^2 \left[ 1 - (\lambda_0 / \lambda) \right] \]  

(1.11)

The refractive index variation as a function of duty cycle and the resulting broadband behavior of diffractive elements formed from artificial dielectrics are shown in Figure 1.5

Figure 1.5: (a) Refractive index variation with respect to grating fill fraction and definition of the parameters used in the equations and (b) Prediction of broadband behavior of artificial coded optical diffractive elements
1.3 Narrow-band Spectral Reflection Filters

The power reflectivity of a DBR structure can be expressed analytically as

\[
R = \left( \frac{n_0(n_2)^{2N} - n_s(n_1)^{2N}}{n_0(n_2)^{2N} + n_s(n_1)^{2N}} \right)^2
\]  

(1.12)

where \(n_0, n_1, n_2\) and \(n_s\) are the respective refractive indices of the surrounding medium, the two alternating materials, and the substrate; and \(N\) is the number of repeated pairs of low/high refractive index material. The spectral reflection bandwidth of a DBR filter can be made narrower by modifying a couple of design parameters. As shown in Figure 1.6, the spectral reflection bandwidth decreases with decreasing index contrast.

Figure 1.6: Dependence of fractional reflection and line width upon layer index contrast. (a) The linewidth for a large refractive index contrast is on the order of 100nm for a small number of layers. (b) The fractional power reflected from the structure approaches unity even for 8 periods as the refractive index contrast is increased. (c) To obtain a filter with narrow linewidth, the index difference between the component layers is chosen to be small. (d) A large number of layers are required to obtain the a fractional power reflection close to 1.
The spectral reflection linewidth for a large refractive index contrast (>0.1) is on the order of hundreds of nanometers. The fractional power reflection can be made close to unity with a small number of layers. The curves shown were generated for eight DBR pairs. When the index contrast is made two order of magnitude smaller, the linewidth drops by a similar factor. The fractional power reflection, however, is lower and more DBR periods are required to obtain a fractional reflection close to unity as the refractive index contrast decreases. A structure with eight hundred periods and a refractive index contrast of 0.005 has the same reflectivity as a structure with 8 periods and a refractive index contrast of 0.5. While low contrast structures are well suited for guided wave structures, they are impractical in the case of free space optics due to physical limitations imposed by the fabrication processes. Holographic techniques remain the most promising method for generating volume holograms with the low index contrast structures with a large number of periods. The wide application of volume holograms is restrained because of lack of commercially available holographic materials which meet requirements of the optical system design. Volume holograms recorded in specialty glasses, namely photo-thermo refractive (PTR) glass, have been used to generate narrow spectral reflection with linewidths that are suitable for use in laser cavities [31, 32]. This is, however, an isolated example made possible only in a specific material. The low index contrast can be achieved using a couple of other methods apart from choosing materials forming the Bragg reflector with refractive index values very close to one another. A low index contrast and hence a narrowband reflection can be achieved by etching a low fill fraction grating through the layered structure. The reflection spectrum of a DBR filter with a sub wavelength grating etched through it was calculated using finite difference frequency domain (FDFD) formalism.
The calculated reflection from a layered structure with a linear grating of period 1.0 µm etched as a function of fill fraction is shown in Figure 1.7. As the fill fraction reduces, the index contrast between the layers reduces and as a result the spectral reflection band narrows. For a sub wavelength structure, the effective index of each layer can be calculated using the effective index method (Equation 1). The material index contrast between silicon oxide and silicon nitride is ~ 0.5. For the structure with under consideration the index contrast reduces to 0.12. However, in addition to the narrower spectral band, the loss in peak reflection is significant. The maximum reflection drops from 90% to below 60% as the fill fraction reduces from 0.3 to 0.1. As mentioned before, more number of layers will need to be used to achieve the similar reflection from the low index contrast structure. The effective index of the component layers decreases with decreasing fill fraction (‘mostly air’) structures. The fabrication of such filters is challenging due to the large aspect ratios. The ability to etch high aspect ratio structures ultimately limits the number of layers that can be used in the structure.

More recently, resonant waveguide grating structures have been used to provide narrowband reflection [33]. The basic device structure and concept of these structures commonly known as guided mode resonance (GMR) filters is illustrated in Figure 1.8. Broadband radiation incident upon the device interacts with the grating. The grating diffracts the incident radiation into multiple orders depending upon the period to wavelength ratio. At resonant condition, the grating period is sub-wavelength and the evanescent diffracted orders are coupled into the waveguide that is placed directly below the grating structure. The waveguide supports only leaky modes that are strongly coupled to the zeroth order propagating modes waves at the resonant wavelength allowing for highly efficient energy transfer. The RCWA calculated reflection spectral linewidth is shown in Figure 1.8. The spectral reflection has high efficiency,
narrow linewidth and large side lobe suppression ratios. The spectral reflection follows a Lorentzian line shape [33]. The asymmetry of the line shape originates from the reflection at the multiple facets. The line shape can be made symmetric by changing the grating and waveguide layer thicknesses to match the antireflection condition away from resonance.

Space Variant Guided Mode Resonance filters have been used in a wavelength sensing application [34]. The devices were constructed by patterning and etching a 550 nm grating in fused silica and using this as the master to generate a PDMS mold. The mold was then placed on a blank silica wafer and titanium di-oxide (TiO₂) was deposited. The thickness of the layer was varied across the device with a 1nm variation every 556 periods. The method by which this gradient is generated is unclear. The device was calibrated by illuminating the device with
known wavelengths and correlating the spatial transmission dip to the pixel location on the CCD camera. Due to the large FWHM of the filter design and a 9µm pixel size on the camera, the minimum wavelength steps that could be detected are limited to 5 nm. This device demonstrates a basic application of a space variant GMR based sensor. The space variant GMR can be used for several other applications such as beam shaping and graded reflection mirrors as will be explored in this work. A better more controllable method for varying one of the grating parameters is necessary since deposition techniques have limited applications. The reflection profile is also affected by the range of variation of the grating parameter such as thickness or fill fraction.

![Figure 1.8: (a) The schematic, operating principle and device design of a guided mode resonance filter (GMR). (b) Spectral reflection obtained from a guided mode resonance filter](image)

(b)
1.4 Narrow-band Spectral Transmission Filters

Photonic crystal structures are a class of spectral filters that offer several unique optical functionalities such as omni-directional reflection, ability to engineer dispersion, negative refraction and self collimation [35]. The introduction of a defect in the periodic structure that forms the photonic crystals has several applications. These structures have been used for tight confinement of optical energy within the defect around waveguide bends. Spectral filters based on the incorporation of a defect in photonic crystal structure generate narrow transmission notches in a wide stop band. The position of the transmission notch within the stop band can be tuned by changing optical path in the defect as shown in Figure 1.9. The spectral width of the notch is narrower for higher reflectivity Bragg mirrors. The width of the transmission notch and its location can also be tuned by etching a lattice of holes through the structure of different periods and fill fractions [36].

Figure 1.9: Photonic crystal structure with a defect layer produces a narrow transmission within a wide stop band.
In this configuration, standard Fabry-Perot equations can be used to predict the 1st order spectral response of such an optical filter. The shift of the transmission peak as a function of the spacer thickness can be traced through the manipulation of the standard equations governing the behavior of this type of optical filter. It is possible to evaluate the performance of such an optical filter as a function of the spacer layer thickness in terms of the location of the transmission notch within the stop band. The spectral transmission response of the dielectric multilayer stack is a function of the spectral reflection characteristics of both of the quarter wave mirror stacks on either side of the spacer layer and the index and thickness of the spacer layer itself. In terms of the reflection/transmission, \( R_{1,2} \) and \( T_{1,2} \), of the two dielectric mirrors, the index and thickness of the dielectric spacer, \( n_f \) and \( d_f \), wavelength, \( \lambda \), and the phase difference terms of the complex reflection coefficients from the two dielectric mirrors, \( \delta_{1,2} \), the finesse, \( F \), maximum transmission, \( T_{\text{max}} \), and phase difference term, \( \Phi \), can be defined as follows:

\[
F = \frac{4\sqrt{R_1 R_2}}{1 - \sqrt{R_1 R_2}} \tag{1.13}
\]

\[
T_{\text{max}} = \frac{T_1 T_2}{(1 - \sqrt{R_1 R_2})^2} \tag{1.14}
\]

\[
\Phi = \frac{2m \lambda f d_f \cos \theta}{\lambda} + \frac{\delta_1 + \delta_2}{2} \tag{1.15}
\]

The transmission through the Fabry-Perot resonator with the dielectric spacer in the middle can then be described through the following equation

\[
T = \frac{T_{\text{max}}}{1 + F \sin^2(\Phi)} \tag{1.16}
\]

The maximum transmission occurs when \( \Phi = m\pi \), where \( m = \pm 1, \pm 2, \pm 3 \ldots \). The transmission peak can be described as a function of the spacer layer thickness and its index as,
In the case of this particular filter, it is necessary to maintain a single resonance within the stop band, thus the value of $m$ is set to one. The linear relationship between the location of the transmission peak and the spacer thickness for a given material is evident. These types of optical filters characteristically have stop-bands with a large bandwidth, high transmission efficiency of the transmission peak within it, and the ability to spatially vary the transmission response has been demonstrated. For specific applications such as hyper-spectral imaging, an ideal optical filter must possess these characteristic, but in addition, also have linewidths of the transmission peaks on the order of tens of nano-meters. The line-width and efficiency of these broadband dielectric based filters can be enhanced through an increasing of the number of deposited high/low pair quarter wave layer pairs that make up the DBR mirrors on either side of the spacer layer and altering the index contrast of the materials used as shown in Figure 1.10.

$$\lambda = \frac{2n_jd_j}{m}$$ (1.17)

Figure 1.10: (a) Comparison of the transmission linewidth and stop band for a filter composed of 4 and 6 SiO/SiN pairs on either side of the spacer layer. (b) Transmission through a filter composed of 5 pairs of a-Si/SiO layers on either side of the defect layer.

Space variant transmission filters have been realized by patterning and etching a sub-wavelength array of holes of varying fill fraction or periodicity structures [36]. Since the
effective index of the space variant structures are a function of the fill fraction and period to wavelength ratio, varying these parameters in a quarter wave stack results in reflectivity control. By controlling the reflectivity of the Bragg mirrors on either side of a defect layer that functions as an etalon results in transmission tuning across the device (Figure 1.11). As a consequence, the device has poor performance at low fill ratios since the reflectivity of the stop band reduces significantly. In addition, this method requires complex fabrication processes for filter operation at shorter wavelengths. The aspect ratios of the holes become large requiring advanced etching processes for their realization.

![Figure 1.11](https://via.placeholder.com/150)

Figure 1.11: Schematic diagram of a image array integrated with space variant filters that transmit different wavelengths [36]

Other methods of space variant grating fabrication have used the variation of spacer thicknesses with position as shown in Figure 1.12. High transmission is achieved across the stop band without deterioration in stop band width or strength [37]. Since etching is not a criterion in this design, the number of layers that form the DBR structure can be made larger or smaller.
depending upon the required transmission linewidth and not the process limitations. Though this
technique circumvents the optical and fabrication challenges posed by the previous design, the
technique requires multiple patterning and etching steps for filter fabrication. As total number of
discrete transmission wavelengths increase, the fabrication complexity grows considerably
requiring multiple intermediate processing steps that may lead to reduced yield and process
fidelity. Space variant gratings have been used for the realization of wide angle filters that
incorporate a pseudo three dimensional defect that offers a similar optical path length for all
incidence angles.

![Figure 1.12: Unit structure of a space variant transmission filter generated by spacer layer
thickness modulation [37]](image)

1.5 Polarization Filters

Metallic wire grid polarizers have been used widely to preferentially filter the TM
polarization. Such devices are composed of a metallic grating that has a sub-wavelength
periodicity and a 50% duty cycle. The operation of the grating can be easily understood by
considering the fact that the polarization parallel to the grating grooves are absorbed due to the fact that they have the ability to induce currents in the device whereas the polarization perpendicular to the grooves induce dipoles that cause re-radiation. Such devices are important in a host of applications from spectroscopy to advanced imaging. More recently, wire grid polarizers that have an integrated antireflection structure that is formed by etching a phase grating prior to metal deposition have been proposed [38]. Such gratings have a broadband response as shown in the Figure 1.13.

![Figure 1.13: Simulated performed of broadband dual layer wire grid polarizer [38]](image)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>264 nm</td>
</tr>
<tr>
<td>b</td>
<td>216 nm</td>
</tr>
<tr>
<td>d</td>
<td>1380 nm</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>2000 nm</td>
</tr>
<tr>
<td>(f)</td>
<td>0.45</td>
</tr>
</tbody>
</table>

The gratings can be fabricated by patterning and transfer etching a linear grating to a quarter wavelength depth and using a directional metal deposition process such as a electron beam evaporation to achieve deposition on the top and bottom of gratings alone. A space variant functionality has been provided by orienting the arrays of linear wire grid or sub wavelength dielectric polarizers for imaging applications and far field polarimetry [39, 40]. Polarization control and conversion has been achieved using sub wavelength gratings. At the sub wavelength scale, such structures provide differential phase retardation to the orthogonal polarizations and have been used in polarization converting elements. By changing the orientation of the grating
structures, the optical axis of the gratings are manipulated to provide differential phase retardation to orthogonal polarization components resolved on a Cartesian grid that is defined parallel and perpendicular to the local orientation. Both quarter wave and half wave designs have been explored and implemented. For conversion of linear to azimuthal polarization conversion using quarter wave design, additional vortex elements are required. In the case of half wave designs as shown in Figure 1.14, the device performs the conversion of polarization completely. Conversion of radial to azimuthal and vice versa has been implemented by several groups [41, 42].

Figure 1.14: Polarization converting elements fabricated by Autocloning techniques [41]

1.6 Research Overview

The objective of this research effort is to develop 3D nano optical elements with unique optical properties. This includes the realization of space variant structures that enable control of the phase, polarization and spectral response of the incident radiation. The realization of nano-optical elements relies on the ability to design and fabricate such elements. Several of the simulation tools required for such an effort have been developed in prior research [16, 41, 43]. This tool set will be applied to the design of new elements for targeted applications. It is also the
goal of this research to develop novel fabrication technologies to realize such structures with a wafer based approach as opposed to the existing serial techniques that are currently in use. Nano-optical elements (NOES) combine functionality of micro and diffractive optical elements with the optical properties of nanophotonic structures like photonic crystals. NOES can enhance performance of devices by providing a means to circumvent fundamental limitations imposed by conventional materials. Novel devices with multiplexed optical functionalities will also be explored.

Filter Elements with Engineered Defect (FEED) layers enable control of the spectral and spatial transmission profile. A novel method for the realization of such elements has been developed by structuring the defect layer incorporated in a one-dimensional photonic crystal structure with analog and diffractive optical elements. In Figure 1.15(a) an example of a lens array patterned and etched into the defect layer is shown. The spectral transmission is dependent upon the local thickness of the defect layer. The spatial transmission profile follows the contours of equal defect layer thickness and is composed of annular rings of wavelength dependent diameter. Arbitrary phase profiles can also be used to pattern the defect layer that has applications in pupil filters for advanced image, wavelength discriminating arrays and tailored illumination systems. Such elements can also be applied to the realization of mirrors with graded amplitude and phase profiles.

Figure 1.15 (b) shows the schematic of a variable fill fraction grating structure which when coated with metal and operated in Littrow condition can be used to provide space variant reflectivity for beam quality enhancement of broad area laser diodes (BALD). As reviewed earlier, gratings have been used to provide optical feedback to laser systems including solid state, gas and diode lasers. The novelty of our approach lies in the fact that the spectral mirror and
beam shaping functionalities are multiplexed. Compact laser diodes that are suitable for high power operation can be realized for applications to second harmonic generation, two photon combining, high power laser arrays for beam combining and laser machining. The loss in reflectivity and the consequent loss in operation efficiency can be offset by the improvement in beam quality and the ability to focus to a diffraction limited spot.

Guided mode resonance filter based space variant optics for beam shaping, graded reflection mirrors in laser resonators and wavelength and biosensing will be explored. A schematic of such an optical element is shown in Figure 1.15 (c). The location of the peak reflection of a GMRF is a function of the grating fill fraction and the layer thicknesses. Frequency dependent space variant reflection profiles will be demonstrated for the first time, to our knowledge, by varying the grating fill fraction across the incident beam. Designed fill fraction profiles can be created using our novel fabrication method and will potentially lead to advanced optics and novel applications. These elements can control the amplitude, phase, polarization and spectrum of the reflected and transmitted beams.
1.7 Dissertation Outline

Nano optical elements are constructed at the scale of one wavelength and hence they offer unprecedented ability to manipulate the polarization, phase and spectrum of the incident radiation. The advances in micro fabrication have made the repeatable realization of these optical structures easy and cost effective. Chapter 2 will review some of the methods currently used to create different types of micro optical functions such as gratings, diffractive and analog/refractive optics. This will be followed by a brief overview of techniques for space variant grating fabrication and a detailed description of a novel method for space variant grating fabrication using optical projection lithography that was developed as part of this work in Chapter 3. For the first time, space variant grating fabrication will be demonstrated using optical lithography on a stepper tool. It offers us the ability to create truly analog space variant devices on scales that are suitable for integration in practical systems. This technique was used to create the space variant grating structures described in the rest of this dissertation. Chapters 4, 5 and 6 will describe the concept and implementation of novel micro optical elements developed as part of this work. Each Chapter will begin with a brief background pertaining to the element and intended application. This is done with a view to familiarize the reader with prior art and the current state of the technology. The device concept, design, simulation, specific description of the fabrication methods, and characterization of the device structural and optical parameters will be provided. Chapter 4 presents wavelength tunable spatial filters that combine spatial and spectral filtering properties in a single micro optical element with applications in pupil filtering for advanced imaging applications. Chapter 5 presents the implementation of variable duty cycle gratings that were tailored to provide graded reflection profiles to improve the spatial brightness of broad area laser diodes. Chapter 6 presents the implementation of graded reflection mirrors to
provide spectrally selective continuous graded reflection profiles using guided mode resonance effects for spatial beam shaping and feedback applications.
2 MICRO OPTICS FABRICATION

Classical optics manufacturing technology relies on bulk machining of materials using advanced equipment to cut, grind and polish to realize the required shape. The materials are suitably chosen to provide low absorption in the operating wavelength regimes except in a few applications such as detectors where absorption is fundamental to the device operation. Coatings are then applied to the final optic to enhance the transmission or reflection. The optical elements are assembled into the final system using opto-mechanical mounts and assembly procedures. These methods remain the state of the art for large area optical component (on the meter and centimeter scale) manufacturing for a variety of applications including telescopes, lithographic steppers, aligners and space optics.

The concept of diffractive optics was developed at the MIT Lincoln labs in the 1980s and first presented in a seminal paper at the SPIE. A diffractive element consists of several zones with a maximum thickness corresponding to a phase retardation of $2\pi$. The thickness of the optical element still varies continuously within each zone. Each zone is broken up into multiple levels in the case of a multilevel diffractive. This element takes advantage of micro fabrication technology, namely lithography, to create planar optics over large lateral areas. Lithography is a technique in which ultraviolet radiation passes through amplitude masking patterns and interacts with the photoresist which upon development retains the exposure footprint. While multilevel diffractive optics technology provided the initial impetus towards large scale miniaturization of optics, several advanced techniques and methods have been developed by the community for the realization of refractive optics at the micro scale. Grayscale, half tone and phase mask lithography techniques have been used for the realization of high quality micro-lenses, prisms, pyramids and axicons and other phase elements. This has allowed optics to leverage the high
quality tool set that has been developed to fuel the phenomenal growth of integrated circuit manufacturing. This has made lithography the method of choice for the creation of high fidelity optics at the micro scale. Replication by micro-molding has also been used in the realization of complex micro-optical structures on the wafer scale [44] after generating the master using direct write technologies. A variety of etching methods have been developed to transfer the patterns formed in photoresist to the substrate of choice. These include fused silica, silicon, III-V and II-VI materials and a variety of other exotic materials such as chalcogenide glasses and lithium niobate. The operating wavelength and application dictates the material choice since the properties of each ultimately affects device performance.

In the following sections of this chapter a brief overview of the techniques for the fabrication of different classes of micro optics – gratings, diffractive and refractive structures – are presented. Examples where the method has been used for the realization of space variant structures are outlined where applicable. This will be followed by a detailed description of the methods developed as a part of this research effort for the fabrication of space variant gratings in Chapter 3. Our technique uses projection lithography for the first time, for the fabrication of variable duty cycle gratings. When combined with growth and deposition technologies, 3D space variant structures can be realized. This enhances and improves the existing capabilities and provides a third dimension that can be further explored and exploited.

2.1 Gratings

2.1.1 Ruling of Gratings

Multiple techniques are available for conventional grating fabrication. Ever since their first demonstration in the late 18th century [45], ruling of gratings has evolved into a powerful method to fabricate both one and two dimensional grating structures. Space variant gratings such as
variable fill fraction and variable line space (VLS) gratings have been demonstrated. Several ruling engines are currently in use and these are typically expensive serial techniques for grating fabrication [46]. Classically-ruled master gratings are produced by first evaporating a coating of gold or aluminum onto a highly-polished substrate, and then mechanically burnishing triangular grooves with a precision diamond tool.

The incredible specifications required for the ruling of gratings demand such a high degree of technology, that few facilities in the world are able to produce them. There only about 10-15 successfully operating ruling engines in the world today [45]. Currently, the ruling procedure consists of a diamond blade that is computer controlled to follow and remove material from a specified path. Variations in stage parallelism, displacement, blade quality are monitored and compensated for during the ruling process.

Figure 2.1: Picture of a ruling engine

Great effort was expended in keeping the spacing between successive grooves uniform as a master grating is ruled. Any variations in groove spacing or period were found to produce stray light and imperfections in the spectra. However, it was discovered that a systematic error in the groove spacing/period could result in excellent control over the curvature of the diffracted wavefronts [47]. Such grating, now called variable line space gratings have been successfully
ruled. Ruling a grating is a painstaking, difficult and expensive process and thus most of the gratings used in instruments are more-affordable replicas of the directly ruled master grating. An inventory of masters is typically maintained from which to create replicas of the gratings.

2.1.2 Holographic Lithography

Holographic techniques of grating fabrication have been developed just recently to primarily fabricate standard one-, two- and three dimensional grating structures. This technique uses interference patterns generated from very uniform planar wavefronts to form gratings in a photosensitive material. The interference of two beams generates linear grating, while three and four beam interference generate two and three dimensional grating structures. Interference lithography, as it is also known, is today a very popular technique for the fabrication of 3D grating structures such as photonic crystals. Several different configurations have been used to achieve interference lithography. One of the simplest setup is a Lloyd’s mirror configuration as shown in Figure 2.2. A typical setup consists of high purity laser source and a mirror to deflect part of the beam at a pre-determined angle which also determines the feature sizes that are achieved. Small changes in the phase front of the beam or imperfections in the mirror that lead to the same effect result in non-uniformity and variations in the developed patterns. Pattern fidelity and uniformity over large areas is a primary concern and requires expensive and sensitive instrumentation to ensure repeatability [44]. Multiple beam interference lithography is very complicated and requires very precise alignment and stable vibration isolated setups to achieve high quality structures.
Figure 2.2: (a) Schematic of a holographic exposure system and (b) Dependence of exposed period on angle of interfering beams

2.1.3 E-beam and Optical Lithography

Lithographic approaches using an electron beam or optical stepper tool are the currently preferred methods to fabricate conventional and space variant grating structures. These techniques have been developed primarily to suit binary fabrication processes as required by the IC industry. The former is a serial scanning method that thus ensures high pattern fidelity and
accuracy and can easily create complex space variant patterns [30]. The latter is a projection imaging tool that creates an image of a binary amplitude pattern placed in the masking plane on the wafer plane. It is reasonably well suited for the fabrication of space variant structures though creation of complex space variant patterns can be challenging. This is due to the varying intensity due to the varying fill fraction which can cause exposure variation resulting in loss of pattern fidelity. This is particularly the case in modern systems that are geared towards high resolution sub-micron lithography that are high numerical aperture shallow depth of focus systems. The following section will provide a more detailed overview of lithographic and general microfabrication methods that are currently in use for fabricating micro-optics.

Electron beam lithography uses an electron beam sensitive resist to generate patterns. The schematic diagram of e-beam lithography system is shown in figure. The electron beam generated from a tungsten or Lanthanum Boride filament or by field emission is collimated and focused using magnets which interacts with the resist and causes a change. While the patterning fidelity is very high, the time and cost of making patterns over large areas is prohibitively expensive. For example, a 200 µm x 200 µm pattern of space variant grating structures takes about 5 hours on a state of the electron beam lithography tool. It is evident that the process does not scale and is suitable for small patterns and prototyping alone.

Optical lithographic techniques processes have been widely used in fabrication of high fidelity gratings over large areas. The process begins with the creation of an amplitude mask that contains the desired patterns that need to be transferred into the wafer. The mask is then placed in contact with a photoresist coated wafer in a contact procedure or in the masking plane of a stepper tool. The contact lithography process is unsuitable for large scale replication since only one repetition of a masking pattern is typically obtained per wafer. This is however a low cost
technique that is suitable for obtaining reasonably large patterned areas. The conformity of the mask-wafer contact plays a big role in pattern fidelity.

A stepper tool on the other hand is a projection system that forms an aerial intensity distribution that replicates the patterns found on the mask. Typically, pattern on the wafer plane is optically reduced as compared to the mask by 4X or 5X. Since the stepper forms an image on the wafer plane, multiple replicas of the same pattern can be obtained on the wafer. The photoresist thus exposed is then immersed in a developer solution that removes the areas that have been exposed in a typical positive tone photoresist. High quality pattern reproduction is typical and modern stepper tools are geared and optimized to achieve this. In the case of g-line (436 nm) and i-line (365 nm) steppers the source is a mercury arc lamp that is configured to provide Koehler illumination. 193-nm stepper tools use laser source that is then scanned across the mask pattern to expose the image on the wafer.

Figure 2.3: Schematic diagrams of electron beam and (g-line) projection lithography system
2.2 Diffractive and Refractive Optics using Optical Lithography

2.2.1 \(2^N\) Patterning and Additive lithography

\(2^N\) patterning and etching techniques were first developed for the fabrication of diffractive optical elements [1]. The technique requires \(N\) patterning, etching and alignment steps for creating a diffractive with \(2^N\) levels. The schematic of the process flow for the fabrication of diffractive optics using this method is shown in Figure 2.4. The wafer is coated with resist and then exposed with the 1\(^{st}\) pattern leaving a binary pattern on the resist after developing. This is then etched into the substrate. The wafer is again coated with resist and the 2\(^{nd}\) pattern is aligned to the 1\(^{st}\) etched pattern on the resist and exposed, developed and the wafer etched. The method is tedious and prone to fabrication errors due to alignment.

![Figure 2.4: Schematic representation of a 2N technique for the fabrication of diffractive optics.](image)

2.2.2 Additive Lithography

Fabrication of multilevel structures in the photoresist depends on partially developed photoresist achieved by partial exposure of the resist. Photoresist sculpting using additive lithography is done by using a set of binary amplitude mask patterns and simple exposure dose
control. In order to do this it is necessary to understand the exposure response of the photoresist. This is given by the contrast curve of the photoresist which is engineered to be nonlinear to improve resolution.

The contrast curve for a general photoresist has three regions on the curve

- A slow response region below a threshold time corresponding to threshold energy.
- A fast rising region between the threshold and saturation; this could be linear or nonlinear depending on the resist
- A saturation region where the resist is completely bleached.

Additive lithography utilizes the 2nd region of this curve, the working region and depending on whether it is linear or non linear different masking techniques can be employed. The first step in the fabrication of multilevel elements using additive lithography is the biasing of the photoresist which is performed by exposing an open aperture of the size of the diffractive to be fabricated. The exposure time for the masking patterns is then calculated either from the slope or from the polynomial fit obtained from the curve. An analog optical structure can be transformed into a diffractive structure by subtraction of multiples of the wavelength ‘$\lambda$’ from the optical path. The resulting structure is still analog. This is then approximated by a multilevel structure by applying a staircase approximation to this analog surface. This can then be split into multiple masking patterns addition of which would lead to the desired multilevel diffractive structure. For fabricating an 8 level diffractive we will need 3 masking patterns. Figure 2.5 shows the additive process with such a masking technique.
Figure 2.5. Additive lithography process using entire domain masking.

For a lens these patterns extend over the entire aperture of the lens and as can be seen addition of exposures for the same mask pattern occurs over two different points on the curve. If the resist is non linear in the 2\textsuperscript{nd} region the resultant heights would be unequal leading to an undesired resist profile. Thus it is necessary in the employment of such masking procedures to use a resist with a linear ‘additive’ region.

2.2.3 Analog Optics Technologies

Analog optics have been fabricated using variety of techniques ranging from grayscale lithography to half toning and reflow. Prior research in the group has resulted in the development of a novel phase masking approach using spatially varying phase gratings for modulating the intensity of the 0\textsuperscript{th} order in the desired spatial function. The method places a phase grating structure in the masking plane of a g-line stepper tool. The period of the phase grating is small
enough to cut off the higher diffraction order. In this configuration, only the 0\textsuperscript{th} order is transmitted through the imaging column to the wafer plane. The intensity of the transmitted order is a function of the fill fraction of the phase grating as shown in Figure 2.6. The thickness is chosen to provide a $\pi$ phase depth at the illumination wavelength. A deviation from this thickness reduces the transmission contrast that is seen in this curve due to a non-zero value at the 50\% duty cycle value.

\[ A_{\text{mask}} \leq \frac{M\lambda}{(1+\sigma)NA} = 3.8\mu m \]

Figure 2.6: Duty cycle dependence of 0th order diffraction efficiency of a phase grating [48]

### 2.3 Transfer Etching

Etching is the selective removal of material from a substrate to create elements with desired functionality. Chemical methods of etching are used in several fields such as diamond polishing, glass fabrication, lithography, MEMS, integrated circuit manufacturing and micro and nano optics. All chemical etching depends on the creation of reactive species that can react with the material of the substrate chosen and form by-products that can be removed from the reaction site
so that fresh material can be exposed. Several methods can be employed to enable this. The two
most popular methods, in recent years, have been wet etching and dry etching and each of these
can be further classified depending on the etching mechanisms and the chemistries chosen. These
techniques have been extensively used to transfer the lithographically patterned optical functions
into the substrates of choice.

Plasma based dry etching can be used to directly create some novel micro optical elements
using techniques such as etch morphing. Morphing is a method by which the selectivity of the
etching of the masking material to the substrate was changed as a function of etching time. The
technique is especially useful in the case of reflown structures. Polymer reflow creates patterns
that are spherical in shape. Etch morphing has been used to create optical functions that have a
different shape in the material post etching.

2.4 Summary

As outlined in this chapter, optical fabrication technology has developed and matured over a
number of years. Ruling of gratings, one of the oldest techniques for grating fabrication,
provides large area gratings with high fidelity. It is a serial process and does not compare
favorably with the methods that have been developed more recently. Machining remains the
popular method for fabrication of lenses, prisms and other refractive components on the
millimeter scale and larger. However, lithography and microfabrication are the methods of
choice for micro optics since they provide the flexibility, scaling and ease of manufacturing
necessary for adoption. In the last few decades, all classes of optical components including
gratings, diffractive and refractive optics, spectral filters, and thin film optics have been
demonstrated by combining lithography with etching and deposition processes. The fabrication
of optics using microfabrication techniques has borrowed and benefited from the explosive
growth in instrumentation and tooling created for manufacturing integrated circuits. Once these fabrication processes were widely adopted a new classes of optics that manipulate the optical radiation at the micro/nano scale were developed. The following chapter describes a novel method developed as a part of this research effort for the fabrication of space variant optics using projection optical lithography.
3 SPACE VARIANT STRUCTURES USING PROJECTION LITHOGRAPHY

Space variant periodic structures have been widely used in optical devices. They provide novel optical functionalities and improved performance. In the case of grating structures formed at the sub-wavelength scale, the effective refractive index of a grating layer is a function of the grating period-to-wavelength ratio and the fill fraction. The effective refractive index dependence on the duty cycle of a periodic structure, has been exploited in spatially varying elements, to realize broadband response in diffractive optical devices (DOE) such as blazed grating structures [29, 49]. The phase retardation of a blazed grating is achieved by varying the effective refractive index across the element, instead of modulating the thickness of the structure. By varying the fill fraction in a regime that provides the same differential phase retardation across the element, for a certain desired range of wavelengths, the blazed grating can be optimized to perform with very high efficiency, over a broader wavelength-band in comparison to classical echelette gratings. By locally controlling the retardation experienced by the orthogonal polarization states at various points in the incident beam, polarization converting elements have also been realized [41, 42, 50]. Apodization or spatial variation of the filling fraction of sub-wavelength grating-based filters such as Distributed Bragg Reflectors (DBR) has been shown to improve the optical response by improving the side-lobe suppression ratio [51, 52]. Sub-wavelength structures with spatially varying duty cycles have also been employed for encoding phase functions in holograms for encryption applications [53].

Several techniques are currently available for the fabrication of optical structures such as gratings, diffractive and refractive micro optical structures. Though some of these methods have been extended to the fabrication of space variant grating structures, robust and flexible
techniques to fabricate space variant optical structures are limited. Space variant optics such as variable fill fraction gratings, curved structures, variable line space gratings are particularly challenging to fabricate.

Table 3-1: Comparison of techniques for Space Variant Grating Fabrication

<table>
<thead>
<tr>
<th>Method/Technique</th>
<th>Pattern Fidelity</th>
<th>Serial/Parallel</th>
<th>Space Variant Patterns</th>
<th>Feature Size</th>
<th>Patterned Area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ruling</strong></td>
<td>Very Good</td>
<td>Serial</td>
<td>Limited</td>
<td>Micron</td>
<td>Very Large</td>
</tr>
<tr>
<td><strong>Holographic</strong></td>
<td>Good</td>
<td>Parallel</td>
<td>Limited</td>
<td>Sub-Micron</td>
<td>Mid-Size</td>
</tr>
<tr>
<td><strong>E-Beam Lithography</strong></td>
<td>Excellent</td>
<td>Serial</td>
<td>Yes</td>
<td>Sub-Micron</td>
<td>Small</td>
</tr>
<tr>
<td><strong>Optical Lithography</strong></td>
<td>Excellent</td>
<td>Parallel</td>
<td>Yes/Limited</td>
<td>Sub-Micron</td>
<td>Mid-Size but Arrays can be made easily</td>
</tr>
</tbody>
</table>

The existing methods are compared in Table 3-1. Ruling of gratings can produce high fidelity smooth gradients in grating period and fill fraction. It is, however, challenging to produce fast local variations and arbitrary gradients in patterns. Ruling is also an inherently serial process and as a result does not scale well. Molding and replication technologies are often used in conjunction with ruling engines for mass production. Holographic lithography is largely limited to the fabrication of gratings structures. The period of the fabricated grating is a function
of the wavelength of source. Complex optical systems are required to ensure the alignments of the various components and ensure repeatability. Space variant gratings with variable depth have been fabricated using holographic lithography. This was demonstrated by using the variable intensity of the Gaussian beam to superimpose a spatially varying intensity distribution upon the high frequency intensity modulation generated due to the interference. The intensity pattern created using this beam produces a variable depth grating in the photoresist.

Electron beam lithography is an excellent method for the fabrication of high quality grating patterns. Grating structures with sub-100nm periods have been reliably demonstrated. The fill fraction, period and depth of the structures have been varied. Fast local variation as well as continuous and smooth gradients in the grating parameter has been demonstrated. Electron beam lithography remains the state of the art in the fabrication of space variant grating structures. Spatially variable duty cycle gratings have been formed mainly using electron beam lithography [29, 49]. It has been coupled with micro molding techniques for mass production. However, electron beam lithography is a serial technique and does not scale well. The patterning time is directly proportional to the desired fidelity of the structures and the total size of the device area. Varying the desired grating parameter in arbitrary patterns, though theoretically feasible, is prohibitively expensive. While optical lithography can replicate space variant gratings created by direct write techniques over large areas, the method lacks the flexibility required for real world implementation. Once the masking patterns are created, they cannot be modified or changed in any manner. As opposed to standard grating structures, space variant optical elements acquire greater functionality when the variable parameter can be modulated in designed continuous gradients over a range of different minimum and maximum values as dictated by design.
3.1 Description of the Concept

We have developed a novel method to fabricate space-variant grating structures, using a simple two step standard photolithographic exposure process. Shipley S1813 photoresist was spin-coated on silicon substrates. Figure 3.1 shows the measured exposure response curve of the resist. A GCA g-line (436-nm) stepper was used to expose the wafers. The latent image of the grating was formed in the photoresist by initially delivering an exposure dose ($t_{\text{grating}}$) that is less than the dose-to-clear value ($t_{\text{clear}}$), for the coating at hand, using a conventional chrome-clear amplitude mask. Subsequently, a follow-up overlay exposure ($t_{\text{ov}}$), using a phase-only mask and the same stepper tool, induced the desired spatial intensity profile variation [48]. The value of the second exposure was lower than the threshold dose of the measured resist response curve ($t_{\text{ov}} < t_{\text{th}}$).

![Figure 3.1: The response curve for a 1 µm thick Shipley1813 photoresist coating is shown. The grating was exposed ($t_{\text{grating}}$) by delivering less than 90% of the saturation dose ($t_{\text{clear}}$). The analog intensity function was then overlaid with an exposure dose ($t_{\text{ov}}$) value less than the estimated threshold dose ($t_{\text{th}}$) such that it will not further expose the resist line areas.](image-url)
The resist was then developed to obtain gratings with spatially varying duty cycles. The fill fraction at any location within the grating structure was dependent upon the local dose delivered from the combined exposure steps. Using the second exposure step to target a window around the optimal exposure dose-to-size for the grating, we were able to preserve the fidelity of the developed photoresist profile, while spatially varying the local feature width.

Figure 3.2: (a) The grating aerial image intensity profile due to the first exposure using the grating amplitude mask is shown. (b) The overlaid analog aerial image intensity profile, from the second exposure and (c) The combination of exposures (a) and (b), results in separating the grating structure in a region with a “nominal” analog bias to the left, and a region with a “high” analog bias to the right of the graphic shown. In the “high” intensity region, the grating grooves
develop thinner than the ones at the “nominal” exposure region. For clarity 10 µm of the spatial extent is shown in all images.

Figure 3.2 shows the grating profile obtained from the two-step exposure method discussed here, compared to the profile obtained from a standard single grating exposure. The total aerial image at the wafer plane is the sum of the intensity profile of the grating mask (Figure 3.2 a) and the analog intensity profile of the phase mask (Figure 3.2 b). The combination of the two separates the grating structure in a region with a “nominal” analog bias to the left, and a region with a “high” analog bias to the right of the image shown. In the “high” intensity region, the grating grooves developed wider than the ones at the “nominal” exposure region. The standard grating line-space = ratio was modulated with proportion to the local cumulative dose variation. By keeping the maximum value of the overlay exposure dose ($t_{ov}$) smaller than the threshold value, we achieved line width modulation without loss in height of the grating structure.

Figure 3.3 further elaborates on the method used to vary the grating fill fraction. The technique that is discussed here does not modify the shape of the line profile significantly. The linear regime and the range over which the exposed linewidth can be varied is extended, without “pinching” the resist structure to an apex. The local linewidth of the patterned features is a function to the amount of the local dose received from the spatially varying intensity profile of the overlay exposure. This is achieved due to the analog profile of the second exposure dose, which has no line-space features as the grating exposure did initially. At the upper limit, when the second exposure dose is beyond the threshold of the photoresist, the adjacent features overlap, resulting in development of the entire patterned area. Decoupling the grating latent image formation and the line width modulation steps allows arbitrary fill fraction variation to be achieved. In contrast, for a grating formed with a single exposure, change in exposure dose
causes the spatial dose distribution pattern to be modified resulting in a limited change in line width. If the grating is severely over exposed, in order to force the line width to shrink considerably, the sidewalls will form at an angle smaller than the normal and the grating line will eventually “pinch”, forming triangular cross sections.

Figure 3.3: By using the threshold region to control the combined exposure (tgrating + tov), the line width can be varied over a large range (red lines). In the case that the overlay exposure is greater than estimated threshold (tov > tth), the patterns are washed-out after development, since the entire exposure profile is shifted to values above the exposure threshold (blue line).

3.2 Exposure Model

A mercury arc lamp is used in the stepper and is adjusted to provide a Koehler illumination. The spatial frequencies generated by the mask transmittance function at the pupil plane were calculated numerically using a fast Fourier transform (FFT) computation. Neglecting the partial coherence of the source, this can be represented as, [54]
In the above equations \( H(f, g) \) represents the transfer function of the stepper, and \( G(f, g) \) is the Fourier spectrum of the object amplitude \( g_o(x, y) \) at the pupil plane.

The partial coherence was accounted for by multiplying the object amplitude function, with the plane wave component of the spatial-frequency source-point. The angular extent of the source is represented by the partial coherence factor. For the GCA 6300 stepper used in this work it was taken to be 0.6 [55]. The image intensity in the resist was computed by incorporating the depth, as a defocus effect, and the standing wave pattern within the photoresist layer[56]. The photoactive compound concentration (PAC) was calculated from the Dill parameters [57]. The effect of the second exposure is computed by updating the PAC concentration from the result of the initial exposure value. The photo resist development rate function was computed from the PAC using the four parameter Mack model [58], and the final photo resist profile was obtained.

The method outlined above leads to deviations from the actual line widths obtained by experiment [59]. One of the reasons for such deviations is that a real photoresist absorbs the incident radiation resulting in a decreased image contrast and normalized image log slope [60]. We were able to obtain an accurate prediction of the linewidth variation with dose by applying adjusted values for the optimal process parameters extracted from experimental data.

The exposure effect in a high contrast photo resist can be expressed as, [60]

\[
E_x = E_N \left( \frac{1}{I_x} \right)^\gamma
\]  

\( \gamma \)
\( E_N \) is the energy required for the photoresist to be cleared for exposure through a mask less open aperture, \( E_x \) is the optimum energy of exposure for a given dose to size, \( I_s \) is the normalized image intensity for a given pattern and \( \gamma \) is a process parameter that relates the change in development rate function for unit change in exposure energy. For a high contrast photoresist, \( \gamma \) assumes a value very close to unity. The change in feature size for a change in exposure energy can be used to calculate \( \gamma \) experimentally. Using this, we can obtain the experimental value of \( \gamma \) for the photoresist process from the duty cycle to dose curve. In order to convert the simulated aerial image intensity pattern to the resist threshold energy, we used a modified equation,

\[
E_w = E_x \left( \frac{I\left(\frac{w}{2}\right)}{I(0)} \right)^\gamma
\]  

(3.4)

\( I\left(\frac{w}{2}\right) \) is the threshold intensity required for resist exposure using the given pattern obtained from the resist model, and \( I(0) \) is the intensity at the center of the feature obtained from the simulated aerial image intensity. These values are used to predict the required exposure \( (E_w) \) for the desired feature width ‘w’.

### 3.3 Fabrication Process Flow

Silicon substrates were coated with a 1µm thick layer of Shipley 1813 photo resist. One and two dimensional gratings of 2 µm periods were partially exposed in the photoresist, using an amplitude grating chrome-mask, by delivering a dose between 75% and 90% of the saturation dose estimated for the pattern, through a GCA g-line (436-nm) stepper. This dose was designed to be lower than the dose-to-clear \((t_{\text{clear}})\), by an amount of energy smaller than the absolute value of
the dose-to-threshold ($t_{\text{clear}} - t_{\text{grating}} < |t_{\text{th}}| = 0.3s$). Following this, an analog intensity profile generated using a phase-only mask function was overlaid. Details of the mask used to generate the analog intensity profile are found elsewhere [48]. The second exposure dose was chosen to satisfy two important criteria. First, the highest intensity in the overlaid exposure profile was maintained less than the threshold exposure of photoresist ($t_{\text{ov}} < |t_{\text{th}}| = 0.3s$). This was to ensure that the photoresist left unexposed by the first exposure was not removed upon development, to preserve the fidelity of the formed grating without variation in line-height across the device. In addition, enough energy was delivered so that the photoresist in the grating grooves formed by the initial partial exposure was saturated at the point of the minimum exposure intensity required to satisfy the dose-to-size value. The range of duty-cycle modulation was controlled by: a) the exposure dose of the grating, b) the differential intensity of the designed phase grating transmission [48], and c) by the exposure dose delivered during the overlay exposure.

In order to quantitatively compare the modulation effect on the duty cycle with the overlay exposure dose, the experiment was repeated using the grating mask and a clear field mask, to deliver the same values of $t_{\text{grating}}$ and $t_{\text{ov}}$. The second exposure dose ($t_{\text{ov}}$) was kept below the threshold value of the photoresist, as in the case of the phase mask trial. The modulation of the duty cycle with the cumulative exposure dose was measured using a scanning electron microscope (SEM). The measured values were compared with the results of the lithographic model.

### 3.4 Results and Discussion

The correlation between experimental and predicted exposure dose required to form a desired feature-width is shown in Figure 3.4. The curves were generated using a 50% duty-cycle mask. When $\gamma = 0.6$, as estimated from the experimental data, the predicted values of the exposure...
dose-to-size correlate within 3% of the measured values. The range of modulation in duty-cycle with exposure dose is smaller as the grating period increases. At the long period limit, large variations in exposure dose are required to change the duty cycle significantly. The variation in feature size with exposure dose is however independent of the grating period, since the feature-size modulation is dependent upon the partial coherence factor, the numerical aperture of the imaging system and the process parameters of the photoresist. Essentially, the described technique allows the photoresist response to the absorbed radiation and subsequent development, to change from a depth variation to a width variation of the exposed features. By operating in a process-window around the dose-to-clear and using an analog spatial intensity distribution, we were able to achieve uniform variation in grating duty-cycle.

For the case of sub-wavelength grating structures, the dependence of the slope of the feature-width variation with exposure dose to the grating period, allows to change the range and position of the duty-cycle variation for a constant spatial intensity profile. This corresponds directly to a change in refractive index, and the phase depth obtained across the fabricated optical element. The same intensity profile can also be overlaid upon one-dimensional gratings of different orientation to form polarization sensitive apodized gratings.

A comparison of the simulated and experimental results for a one dimensional grating, overlaid with an analog exposure is shown in Figure 3.5. The measured spatial modulation of the duty cycle is in close agreement with our model, with a linear dependence across the element, in accordance with the functional form of the analog intensity overlay. Scanning electron micrographs of the variable fill fraction gratings in the low and high fill-factor areas are shown in Figure 3.5 (c) through (f). The abrupt change in fill fraction of the gratings along the grooves is
due to the transition in the phase-only mask from an area of analog intensity, to an open aperture that passes all of the incident radiation.

![Graph showing feature size variation as a function of exposure dose](image)

**Figure 3.4:** (a) Feature Size variation as a function of exposure dose: experimental and predicted values for process parameter $\gamma = 0.6$ and, (b) predicted dose variation as a function of the grating period, based on the same simulation model.
Figure 3.5: (a, b) Comparison of numerical and experimental results for the duty cycle variation obtained with a one dimensional grating exposure overlaid with an analog intensity function; (c, d) SEM images of the variable fill fraction gratings (e, f) Magnified images of the transition from the phase mask controlled analog intensity region to the open aperture in the low and high fill-fraction regions.
Figure 3.6: The effect of an analog exposure ‘ramp’ profile overlaid on a 2-D grating. (a) As the overlay dose increases, the adjacent holes overlap and the structure transitions from a hole-array to a post-array. (b) Magnified micrographs of the photoresist, taken at a 30° tilt, showing the sidewall and cleared photo resist at different spatial coordinates in the patterns shown in (a). The profile of the structures is slightly conical, with a larger opening on the air side. This is attributed to resist loss during development.

Spatially varying structures were also formed using two-dimensional gratings exposed in the photoresist, followed by the analog intensity exposure. Experimentally, a phase mask with analog intensity profiles that formed index prisms was used. Uniform, analog variation of duty-cycles was obtained. Scanning electron micrographs of refractive prisms formed using spatially-variant grating structures is shown in Figure 3.6. As the fill fraction of the 2D-grating holes increases across the element, adjacent holes merge and the structure transitions into a “post” array. As observed with the linear grating, the photoresist height of the 2D-grating does not
change across the device. As the dose increases from bottom to top in the figure, the adjacent holes overlap and the structure transitions from an array of holes to an array of posts. Magnified micrographs of the photoresist taken at a 30° tilt show the sidewall profile and cleared photoresist height at different locations in the device. The profile of the structures is slightly conical, with a larger opening on the air side. This is attributed to resist loss during development.

![Micrographs of photoresist](image)

![Graphs of duty cycle](image)

Figure 3.7: Quantitative results from the exposures of the 2-D grating of Figure 6. The duty cycle variation range was adjusted by varying the analog exposure dose (tov). The resulting fill-fraction of the grating varied from (a) 0.53 - 0.7 and from (b) 0.6 - 0.8 in the micrographs.

By varying the level of the grating exposure ($t_{grating}$) and the analog profile function ($t_{tov}$) we were able to change the range of duty-cycle variation. The effect of analog exposure time was studied by holding the initial grating exposure dose at 85% of the saturation dose value, and by
delivering different doses of the prism intensity. For the same analog intensity profile, we were able to position and control the duty-cycle variation range as shown in Figure 3.6. The duty cycle was varied between 0.5 and 0.7, and from 0.6 to 0.8, for different overlay exposures. This corresponds to an ability to engineer the effective refractive index range of the fabricated sub-wavelength optical functions. The grating exposure dose delivered can be used to control the central placement of the duty-cycle modulation. Since the duty cycle variation with exposure dose has different linear and non-linear regimes, this effect can be used to realize complex optical functions.

3.5 Sub-Resolution Patterning on the GCA Stepper

The choice of operation wavelengths are restricted by the ultimate resolution of the lithographic hardware available to us. The technology was developed using GCA 6300 g-line stepper. The resolution of this stepper can be calculated as,

\[ R = \frac{(1 + \sigma)\lambda}{\text{NA}} \]  

(3.5)

where R is the width of the smallest line that can be patterned, \( \sigma \) is the partial coherence factor of the stepper source (0.38, in this case), \( \lambda \) is the illumination wavelength (436 nm, in this case) and NA is the numerical aperture of the stepper imaging system (0.3, in this case). R was calculated to be \( \sim 1.15 \mu\text{m} \). While this is the theoretical resolution of the stepper system, practical constraints such as photoresist thickness, contrast curve (the difference in dissolution rates between exposed and unexposed photoresist) and light divergence through the bulk of the photoresist result in the actual patternable linewidth to be closer to 1.25 \( \mu\text{m} \). Thus other techniques will need to be used to reduce the lithographically patterned linewidth. We propose to employ a recently developed technique described below. The mask uses gratings that are larger
than the required period. High fidelity patterning of these structures is ensured. By following this initial exposure with an exposure of the same grating, just shifted in the appropriate coordinates, we can obtain gratings of the required period. The success of this technique depends on the stage resolution and alignment accuracy between the different levels. The stepper system has a stage overlay accuracy of 100-nm and an alignment tolerance of 150 nm. These values can be significantly reduced by the use of appropriate patterning procedures. Some of the initial results from this patterning are shown in Figure 3.8. Overlay accuracy of ~20 nm was achieved consistently.

Figure 3.8: 1 µm period grating structures obtained on the GCA g-line stepper by double patterning a 2 µm period grating in 1µm thick photoresist

3.6 Summary

In this chapter a simple, low cost, high-fidelity process for the fabrication of space variant optical structures was described and demonstrated. A method for theoretically predicting the feature size as a function of local exposure dose was developed. The effect of local dose variation was quantified experimentally using a dose vs. duty cycle curve. The effects of the process parameters were used to refine the numerical model, and the predicted results closely matched our experiment. The fabrication methodology developed allows control over the placement, range and limits of duty-cycle variation in 1D and 2D-grating structures, enabling
more challenging designs to be realized easily and cost effectively. By combining this method with various approaches to generate analog intensity overlay profiles, enables the design and implementation of artificial-index optical function devices. The ability to fabricate large scale space variant gratings can lead to their use in practical applications. This technique was used to fabricate space variant guided mode resonance based mirrors described in Chapter 6 and graded reflectivity Littrow gratings for spatial brightness enhancement of broad area laser diodes as described in Chapter 5.

Sub-resolution patterning of grating structures on a g-line stepper was also developed and demonstrated. Using this technique, grating periods of 1µm can be reliably fabricated compared to standard lithographic resolution of 1.15µm. Though the resolution enhancement may not appear significant, the quality of the gratings fabricated at this resolution is a significantly better. This allows the performance of the optical filters to closely match design.
4 MICRO OPTICAL SPATIAL AND SPECTRAL FILTERS

4.1 Introduction

Spatial transmission filters in imaging systems improve or enhance the information collected from a scene. The spatial filters have been introduced in the pupil plane and, in the case of modern CCD based imaging systems, on the image sensor side. The form and shape of the pupil plane filter has a strong influence on the shape of the focal caustic. Amplitude and phase pupil filters have been studied widely with a stated goal to engineer the point spread function obtained in the imaging plane. The reduced in transverse spot size and the increased axial depth of focus obtained from amplitude or phase annular pupil filters are well known [61]. The ratio of the diameter of the central obscuration to the full aperture controls the radial and axial point spread function distribution. Larger obscurations produce small radial spots and increased axial focus. The power transmitted through the system decreases with increasing obscuration. Figure 4.1(a) shows an image of a annular filter array placed behind the lens let array of Shack-Hartmann wave front sensor to improve the resolution and sensitivity of the wave front slope measurement [62].

![Figure 4.1: (a) Annular pupil filter array used to enhance the resolving power of a Shack-Hartmann wavelength sensor (b) Different polarization matched orientations of a wedge spatial filter used to improve the patterning fidelity in a high numerical aperture lithographic projection imaging system](image_url)
Other types of amplitude pupil filters have also been studied. Figure 4.1(b) shows a wedge shaped spatial filter to improve the patterning fidelity of a high numerical aperture lithographic system [63]. The orientation of the features on the masking reticule impacts the patterning fidelity on the wafer plane for high numerical aperture projection lithography systems. Under polarized illumination, masking patterns that are orthogonal to the direction of polarization are imaged better than patterns that are parallel. The orientation of the wedge filter was coordinated with the direction of polarization to obtain optimal imaging for all feature orientations. The spatial frequencies that are aligned to the transmissive sections of the filter are preferentially imaged while the orthogonal frequencies are blocked. A two step exposure technique with the filter rotated to match the polarization direction was carried out for optimal patterning of all features on the masking reticule. Other methods to obtain information about the nature of the object under observation using a given optical system have been explored. Multispectral imaging techniques have been used in a host of applications for object recognition, target acquisition, skin imaging for cancer detection and other applications. One of the earliest methods of multispectral imaging is the use of high frequency Dammann phase gratings to obtain multiplexed spectral imaging [64]. The grating dispersion produces multiple images different colors around optical axis. The introduction of Fresnel Zone Plates (FZP) structures in the pupil plane has been shown to extend the depth of focus by producing multi-color images along the axis. Acousto-Optical tunable filters have been widely used for multispectral imaging for detecting the spectral and polarization signature of the object under observation [65]. These imaging systems have.

More recently, optical interference filters have been used to spatial tune the transmitted spectrum for direct integration onto image sensors. The basic configuration of an optical
interference filter is designed to achieve a transmission notch within the stop band of a photonic crystal structure [66, 67]. A schematic cross section of the spectral filter is shown in Figure 4.2. Typically these filters are composed of two materials of high and low index deposited in alternating quarter-wave thick layers. As discussed in Chapter 1, the reflection bandwidth is a function of the index contrast between the two materials used to create the alternating structure. The intensity of the transmission stop band is a function of the number of layers used to create the structure. When a defect layer is introduced in this structure, a transmission notch is generated. These filters have high transmission with excellent side-lobe suppression. The spectral width of the transmission notch is primarily a function of the reflectivity of the distributed Bragg reflector (DBR) mirrors and its location within the transmission stop band is a function of optical thickness of the defect layer [68]. The transmission line can be tuned across the stop band continuously by varying the optical thickness of the defect layer.

![Figure 4.2: Cross section of DBR spectral filter](image)

Space variant functionality has been achieved by patterning and etching a sub-wavelength array of holes through an alternating multilayer stack of PECVD grown Silicon Oxide (SiOₓ) and Silicon Nitride (Si₃Nₓ). By changing the fill fraction or lattice constant of these subwavelength gratings at discrete spatial locations, the optical thickness of the defect layer was varied [36, 67]. This approach has the advantage that growth and patterning/etching steps are decoupled. As a result the wafer does not have to be removed from the growth chamber during the fabrication process. When the transmission notch location is tuned by varying the fill fraction of the gratings, the effective index contrast between the layers is reduced at smaller fill fractions. This
adversely affects the stop band width, the effective reflectivity of the DBR mirrors and as a consequence spectral linewidth of transmission. The fabrication such filters for visible wavelengths is a challenging proposition given the size and aspect ratio of the holes that are required [69]. Transmission filters for direct integration on to an image sensor have been demonstrated at visible wavelengths by spatially modulating the physical thickness of the defect layer [37]. The device performs well for transmission centered across the entire stop band since the mirrors reflectivity remains constant. Discrete wavelengths in the incident broadband radiation that achieve a $2\pi$ phase retardation are alone transmitted. In this approach, the defect layer was patterned and etched using a $2^N$ patterning and etching approach that requires multiple alignments, lithography and etching steps. This ultimately limits the number of discrete transmission wavelengths that can be obtained. Theoretically, the transmission can be tuned continuously across the stop band.

Different aperture functions offer different enhancements to the system performance. In the case of multispectral imaging systems, the dispersive element used in the pupil plane may be a filter wheel, grating or prism and the spatial separation thus generated is detrimental for compact system considerations. Wavelength tunable spatial filters can provide an alternate approach for combining the improvements that can be achieved from spatial filtering and multiplexed spectral imaging configurations. There is a need for novel optical components that can be used for such scenarios. The transmission through a optical interference filter can, theoretically, be tuned across the entire stop band. In practice, the continuous tuning can be achieved by incorporating continuous phase functions in the defect layer. Thus, by combining the unrelated fields of spectral filtering and micro optics, wavelength tunable spatial filters can be realized. The schematic diagram of the optical component envisioned is shown in Figure 4.3.
component will thus provide wavelength dependent spatial apertures that can be used under broadband illumination to obtained enhanced spectrally multiplexed images. Under narrowband illumination combined with sequential illumination, these components can be employed to generate image sets that can be computationally combined to create a single super resolved image [70].

The near-field spatial profile of the transmission can be tailored using defects with designed spatial thickness profile. By incorporating diffractive and refractive phase functions in the defect layer, both discrete and continuous spectral transmission tuning as a function of location can be achieved. Since the transmission notch results when the accumulated phase of the radiation propagating through the structure equals zero, the spatial transmission profile obtained from these structures will correspond to the contours of equal optical thickness across the defect layer. As a result, such devices will achieve wavelength dependent spatial filtering of the transmission at each spectral location across the tuning range. The schematic diagram of an 8-level, charge 2 (the height of the vortex goes from maximum to minimum every 180°), diffractive vortex lens

Figure 4.3: Schematic diagram of the proposed filter elements with engineered defect layers for spatial and spectral control of transmission
and refractive micro lens array incorporated on the defect layer are shown in Figure 4.3. In the case of the former, 8-discrete transmission wavelengths will be obtained as a function of thickness of each level of the vortex. The spatial illumination profile at each wavelength will consist of triangular regions separated angularly by 180°. Each micro lens in the array and the entire array will provide a continuous tuning of the spectral linewidth. When a single micro lens is illuminated the spatial profile will consist of annular rings of wavelength dependent diameter. Illumination of the entire micro-lens array will result in annular rings spaced at the period of the array. These filters represent a novel application of interference spectral filters since they multiplex spatial and spectral optical functionalities.

These novel classes of optical filter elements have several applications. Filters of this kind have been implemented in the image plane for spectral filtering and color detection. Annular aperture based spatial pupil filters have been widely used in projection lithography systems, telescopes, and confocal microscopy [71-74]. It is well known that the three-dimensional PSF of annular apertures have properties that are different from standard circular stops. Broadly, the transverse point spread function (PSF) in the Gaussian image plane profile is narrowed while the axial profile is larger by a factor that is dependent upon the obscuration ratio as compared to the airy profiles. The following sections will discuss the numerical modeling and fabrication of filters for two wavelength regimes – the 3-5µm and 1.5 - 1.6µm (optical C and L band) regimes. The challenges in the fabrication and testing of these devices will be described in detail. The devices with patterned defect layers were realized for both operating wavelength regimes and the experimental results will be compared with the numerical simulations.
4.2 Numerical Analysis

A materials survey was performed to identify the materials system to be implemented in this work. For more accurate simulations and design, the numerical codes were adapted to incorporate the dispersion data for the constituent materials. Silicon (Si) was chosen for the substrate material due to its low loss in the thermal infrared. Other available substrate materials include fused silica and gallium arsenide. Silicon has cubic (F-43m) symmetry making it isotropic. It has a refractive index near 3.4 with negligible loss for wavelengths longer than 1.1 μm. To account for its dispersion, the Sellmeier equation given as

\[
n^2(\lambda_{\mu m}) = 1 + \frac{10.66842933 \cdot \lambda_{\mu m}^2}{\lambda_{\mu m}^2 - (0.3015116485)^2} + \frac{0.003043475 \cdot \lambda_{\mu m}^2}{\lambda_{\mu m}^2 - (1.13475115)^2} + \frac{1.54133408 \cdot \lambda_{\mu m}^2}{\lambda_{\mu m}^2 - (1104.0)^2}
\]  

(4.1)

where \( \lambda_{\mu m} \) is the free space wavelength in micrometers.

Silicon nitride (Si\(_3\)N\(_4\)) and silicon monoxide (SiO) were the first materials considered to form the multilayer substrate. The refractive indices of the two chosen materials (low index SiO\(_x\) and high index Si\(_x\)N\(_y\)) were characterized on a Woollam VASE ellipsometer. Both the growth rate and wavelength dependent refractive indices of the films were measured. This ellipsometer reaches its cutoff around 1700 nm, so the obtained Cauchy coefficients were used to extrapolate the data to the wavelength range of interest. The refractive indices for the silicon oxide and silicon nitride films are provided in Figure 4.4. At 4.0 mm, the refractive index of SiO was 1.4435 while for SiN it was 1.9332.

SVPC filters were designed by engineering a stack of dielectric layers. As mentioned before, the spectral filters are essentially distributed Bragg gratings (DBRs) composed of alternating layers of low index and high index materials with a defect layer included to produce a narrow transmission notch within the stop band. From the obtained ellipsometer data, the SiO layers were made 693 nm thick while the SiN layers were made to be 517 nm thick. A defect layer of
SiO was placed between a top and bottom DBR which was composed of 6 pairs of the alternating high and low index films. In this configuration, the DBRs provide a wide stop band while the defect layer produces a narrow transmission notch within the stop band that can be tuned in wavelength by adjusting its thickness. The number of pairs was chosen to maximize the transmission since the detection schemes at these wavelengths do not have high sensitivity. For the devices operating at the 1.55 µm regime, structure had eight pairs of 265 nm thick oxide and 199 nm thick nitride layers forming the distributed Bragg reflector (DBR) mirrors on either side of the oxide defect layer.

![Graphs showing refractive index vs. wavelength for SiO and SiN films for different wavelength regimes.](image)

Figure 4.4: Refractive index of the PECVD grown SiO film and SiN films for the (a) and (b) 1.55 µm regime and (c) and (d) for the 3-5 µm regime.
The spectral response of the SVPC filter was calculated using RCWA and the results are shown in Figure 4.5. The left plots show a continuous tuning as thickness of the defect layer is increased for either wavelength regime. The right plots show discrete transmission spectra for five different defect layer thicknesses. These simulations show that transmission can be tuned across the entire width of the stop band.

![Figure 4.5](image1.png)

Figure 4.5: (a&c) Transmission through the SiO/SiN device as a function of defect layer thickness. (b&d) Transmission spectra through the same device for five defect layer thicknesses.

### 4.3 Fabrication of Spatial and Spectral Elements

We have developed an approach to the fabrication of space variant optical devices borrowing from prior research in the fabrication of surface relief multilevel diffractives and the analog
optics [48, 75]. The resist processing methodology is similar to the one described for additive lithography in Chapter 2. The photoresist is first biased to cross the threshold region and the actual exposure through the phase mask creates a phase optic by an exposure dependent resist volume removal on development. It is important to match the phase mask design to the photoresist response curve in the case of non-linear resists. The Figure 4.6 shows the process developed for filter fabrication. A bare silicon wafer was cleaned in a solution of sulfuric acid and hydrogen peroxide to remove any organic residue. The wafer was rinsed in de-ionized (DI) water, blow dried with nitrogen, and placed in an oven to dry. The bottom DBR was grown onto the silicon substrate using plasma enhanced chemical vapor deposition (PECVD) on a Surface Technology Systems (STS) tool.

![Figure 4.6: Schematic of the space variant transmission filter fabrication by defect layer thickness modulation](image)

As per design, multiple pairs of silicon oxide (SiO$_x$) and silicon nitride (Si$_x$N$_y$) were deposited followed by a defect layer of SiO$_x$ were grown and the wafer was removed from the growth chamber. Shipley 1813 positive photoresist was spin coated onto the substrate with the deposited layers to a thickness of 1.2 µm. Additive lithography was used to form multilevel structures on the spin cast photoresist on a GCA 6300 g-line stepper tool. The desired surface
relief phase function was patterned in the photoresist followed by development. The thickness of photoresist left behind post development in each individual pixel was varied by changing the dose delivered during the exposure. The exposed photoresist was immersed in developer solution to create the space variant optics.

The patterns formed in photoresist are transferred to the defect layer by dry etching in a Unaxis Versaline oxide etcher using CHF$_3$/O$_2$ plasma chemistry. The selectivity of etching is defined as the ratio of etched oxide to the etched photoresist. Since the fabricated micro optics have a low sag (on the order of 500nm or less) a low selectivity process is required to transfer the patterns formed in photoresist which typically is spin coated to a thickness of 1 µm. Though resist formulations that provide lower thickness are available, the creation of continuous surface relief and diffractive optics are more challenging at lower thicknesses due to higher contrast of these thinner formulations. In addition, any spatial variation in exposure dose and back reflections from the substrate cause roughness in the fabricated structures. Etching selectivity was varied by changing the amount of oxygen in the plasma chemistry as shown in Figure 4.7. The percentage of oxygen affects the photoresist etch rate linearly while the oxide etch rate varies from 200 nm/min for no oxygen flow in the chemistry to 180 nm/min for 90% oxygen in the flow mixture. A selectivity of 0.7 was used to transfer etch the photoresist patterns.

The above etching process leaves behind a nano-layer of Teflon-like material that must be removed before growing the top DBR. This is removed by immersing the wafer in a solution of sulfuric acid and hydrogen peroxide and then exposing the wafer to oxygen plasma to clean any remaining debris. This ensures conformal growth on the surface of the wafer. In this work, multilevel square arrays, diffractive structure and analog micro-optical elements were used to pattern the defect layer. Each of these elements has a discrete wavelength dependent
transmission profile that follows the contour of equal defect layer thickness. Thus both the spectral and spatial characteristics can be controlled using the optical devices.

Figure 4.7: Etching selectivity of silicon oxide in a CHF3/O2 plasma as a function of percentage of oxygen in the chemistry. The curves were generated empirically on a Unaxis Versaline oxide etcher using an ICP power of 600 W and an RIE power of 80W at an operating pressure of 10mTorr.

A bare silicon wafer was cleaned in a solution of sulfuric acid and hydrogen peroxide to remove any organic residue. The wafer was rinsed in de-ionized (DI) water, predried by blowing with nitrogen, and placed in an oven to fully dry. The bottom DBR was grown onto the silicon substrate using PECVD on a Surface Technology Systems (STS) tool. To realize the design, six pairs of 693 nm thick SiO and 517 nm thick SiN layers followed by a 1210 nm thick defect layer of SiO were grown and the wafer was removed from the growth chamber.

Shipley 1813 positive photoresist was spin coated onto the processed wafer to a thickness of 1.2 µm. Additive lithography was used to form multilevel structures into the spin cast photoresist on a GCA 6300 g-line stepper tool. Each pixel on this wafer was 1.0 mm². Thickness of the photoresist left behind after development was varied over each pixel by adjusting the dose delivered over each pixel during the exposure process. The exposed photoresist was immersed in developer solution to create the space variant optics. The patterns were transferred into the defect layer by dry etching in CHF3/O2 plasma chemistry with a 1:1 selectivity using a Unaxis Versaline plasma based dry etching tool.
A first wafer was fabricated with several 3×3 pixel arrays. Heights of the pixels were measured using a DekTak profilometer. The roughness of the samples was measured using an atomic force microscope. These measurements are summarized in Figure 4.8 for one of the arrays. The top DBR was then grown with the same process as the bottom DBR. Microscope images of the wafer and close-ups of the formed structures are provided in Figure 4.9.
Other micro-optical structures were fabricated into the defect layer of spectral filters. These were 8-level, charge 2, vortex lenses and analog micro-lens arrays. An illustration of a vortex lens fabricated for this effort is shown in Figure 4.10. Micro-lens arrays are finding applications in computational imaging systems such as integral imaging where true stereographic data is captured from planar devices.

4.4 Results and Discussion

4.4.1 Spectral Transmission Tuning

To confirm the spectral tuning concept a second wafer was fabricated that contained much larger pixels for testing. Transmission through these pixels was measured on a Nicolet FTIR spectrometer. The layout of the wafer with its stop band centered at 4.0µm is shown in Figure 4.11.
4.11. The wafer was coated mostly with chrome with 1 cm square apertures formed around each square pixel. The pixels themselves were 5 mm along each dimension.

During testing, it was extremely difficult to align the FTIR beam exactly to the center of each pixel and to collimate the beam so that it only illuminated the pixel regions. For these reasons, a portion of the beam fell outside of the pixel regions as illustrated. As a consequence, the measured transmission spectra were a combination of the pixel transmission $p_{\text{mm}}(\lambda)$ and background transmission $b(\lambda)$. Given the fraction $f$ of the beam transmitted through the pixel area, the combined transmission $T(\lambda)$ was

$$T(\lambda) \approx f \cdot p_{\text{mm}}(\lambda) + (1 - f) \cdot b(\lambda)$$

(4.2)

![Figure 4.12: Interpretation of experimental results](image)

A simulated example is provided in the right diagram of where three transmission curves are shown. The red line with long dashes shows the transmission of the pixel region alone. The blue line with short dashes depicts the pure background transmission observed outside of the pixel regions, but inside the chrome apertures. Using Eq. (32) with $f=0.6$, the black solid line estimates...
the combined transmission spectra when both regions are partially illuminated. Both transmission peaks are present with the total transmission of each reduced by nearly 50%.

Figure 4.13. FTIR transmission data of 4×4 pixel array showing strong tuning response

The raw transmission data measured in the lab is provided in Figure 4.12, where the transmission is plotted versus wavelength for the sixteen pixels on the wafer. The raw data shows two transmission peaks as predicted above due to measuring a combination of both the pixel and
background transmissions. While inconvenient in some regards, the presence and shape of both transmission peaks indicates that all pixel filters were well formed. If the underlying films were deformed or distorted in any way around the pixel boundaries, the transmission peaks would have been considerably weaker and broadened. A weak and broad peak around 4.4 µm was present due to a dispersion anomaly of the SiN material.

To isolate the pure spectral response of the pixels, the background transmission was numerically removed. This transmission data is provided in Figure 4.13 and clearly demonstrates the ability to uniquely tune the spectral response of each pixel across the array.

4.4.2 Spatial Transmission Tuning

In order to study the spatial transmission profiles of the devices, another set of devices were fabricated with layer thicknesses of the Bragg mirror corresponding to a stop centered at 1550 nm. The defect layer was patterned with diffractive vortex elements and analog lens arrays. The devices were interrogated with a tunable laser source that operates from 1520 nm to 1630 nm. A fiber collimator producing a 380 µm beam was used to couple the light to the devices. In the case of the vortex elements, the spectrum was measured on the discrete levels.

The profilometer measured levels and roughness corresponding to each of the 8-levels in the diffractive are summarized in Table 4-1. The maximum roughness on any of the levels was 5.5 nm RMS. At this scale, the deposition process will smooth out the variations which are sub-wavelength at the wavelength region of interest. The heights of the vortex levels deviated from the target heights by 10%. While this change would impact the performance of the diffractive optical element significantly, the filter performance would not be impacted significantly since the transmission at these thicknesses are spaced further than the spectral FWHM. The spectral
characterization is summarized in the following paragraphs and compared with numerical modeling.

Table 4-1: Measured level heights of the fabricated diffractive vortex element

<table>
<thead>
<tr>
<th>Vortex Level</th>
<th>Thickness of the defect layer (nm)</th>
<th>RMS Roughness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>500</td>
<td>2.82</td>
</tr>
<tr>
<td>1</td>
<td>425</td>
<td>4.84</td>
</tr>
<tr>
<td>2</td>
<td>372</td>
<td>4.61</td>
</tr>
<tr>
<td>3</td>
<td>310</td>
<td>5.0</td>
</tr>
<tr>
<td>4</td>
<td>268</td>
<td>1.84</td>
</tr>
<tr>
<td>5</td>
<td>232</td>
<td>6.18</td>
</tr>
<tr>
<td>6</td>
<td>150</td>
<td>5.5</td>
</tr>
<tr>
<td>7</td>
<td>70</td>
<td>3.2</td>
</tr>
</tbody>
</table>

The devices were interrogated with a tunable laser source that operates from 1520 nm to 1630 nm. A fiber collimator producing a 380 µm beam was used to couple the light to the devices. The spectrum was measured on the discrete levels of the vortex elements. Four of the vortex levels had defect layers with thicknesses appropriate for transmission in wavelength range of the tunable laser. The results from simulation and experiment are compared in Figure 4.14(b). The transmission notches were located at 1532 nm, 1552 nm, 1575 nm and 1610 nm. The transmission line had a full width half max (FWHM) of 10nm in simulation and experiment.
The transmission through the vortex was imaged on to a CCD camera. The beam from the tunable laser was amplified using an Erbium doped fiber amplifier (EDFA) and the beam diameter was expanded to 3mm. This was done to ensure that large sections of the vortex element were illuminated by the beam. As expected, the transmission through the element was composed totriangular wedges separated by 180 ° with wavelength dependent orientation. The amplification range of the EDFA was between 1525 to 1565 nm and as a result transmission through two of the eight levels was measurable. It is apparent from the images that when the wavelengths are scanned through the tuning range of the device, the wedge patterns will rotate as a function of wavelength. These novel devices have applications in computational imaging, hyper spectral imaging, sensing and as pupil filters apart from detector plane color filtering.
Figure 4.15: Images of the transmission through the vortex element at different transmission wavelengths. The vortex element was illuminated using a beam of diameter 3-mm.

For the analog lens arrays the transmission was imaged on to a CCD camera. Annular rings with wavelength dependent diameters were observed. The width of the annulus was calculated by modeling and measured experimentally. The transmission as a function of defect layer thickness is shown in Figure 4.16. The fabricated analog lenses were 500 nm in height and 250 µm in diameter. It was determined by modeling that a 28nm range of defect thicknesses centered at 265 nm allow transmission of 1548 nm wavelength. The lateral dimension of the aperture was estimated to be 12.5 µm geometrically and agrees well with experimental measurements shown in Figure 4.16 (b). The aperture dimensions were constant across wavelengths since the lenses were shallow. The aperture is a function of the number of layers comprising the top and bottom.
DBRs and the radius of curvature of the patterned lens structure. The aperture size can be made thinner by reducing the diameter of the patterned lenses.

Figure 4.16: (a) The graph shows transmission as function of defect thickness for a constant wavelength used to determine the aperture size. (b) Annular rings of transmission observed by illuminating analog elements.

The transverse and axial irradiance of the PSF is given as [76, 77],

\[
I(0, \rho) = \frac{a^4}{\lambda^2 R^2} \left[ \frac{2J_1(v)}{v} - \varepsilon \frac{2J_1(v\varepsilon)}{v} \right]^2
\]

(4.3)

\[
v = \frac{2\pi a \rho}{\lambda R}
\]

(4.4)

\[
I(z,0) = \frac{a^4}{\lambda^2 R^2} \left\{ \frac{\sin \left[ \frac{P}{2} (1 - \varepsilon^2) \right]}{\frac{P}{2}} \right\}
\]

(4.5)

\[
p = \frac{\pi a^2 z}{\lambda R^2}
\]

(4.6)
where, $I$ is the three dimensional irradiance in Gaussian image plane, $a$ is the radial extent of the aperture and is wavelength dependent in our case, $\lambda$ is the wavelength of illumination which varies in our case, $R$ is the distance of the focal plane from the exit pupil, $J_1$ is the Bessel function of first order, $\varepsilon$ is the obscuration ratio, and $z$ is an parameter that indicated distance along the optical axis.

The parameters of the wavelength dependent apertures were used to calculate the lateral and transverse dimensions of the diffracted spot. The simulated plots are shown in Figure 4.17. The lateral spot diameter at an illuminating wavelength of 1548 nm was $\sim 6\mu$m and the axial spot size was estimated to be 100 $\mu$m. The diffracted patterns were measured experimentally and the results are shown in Figure 4.18. The diffraction lateral spot was measured to be 17 $\mu$m compared to the numerical value of 6 $\mu$m. This discrepancy in the measured spot size is attributed to the relatively large pixel size of 9$\mu$m in the CCD camera used for the imaging. These elements can be potentially applied to spatial and spectral filtering applications such as Fourier domain optical coherence tomography and swept source OCT.

Figure 4.17: Analytically estimated diffraction spot dimensions (a) A lateral spot size of 6 $\mu$m was estimated at a wavelength of 1548 nm and (b) An axial spot size of 100 $\mu$m was estimated.
Figure 4.18: Experimentally diffracted spot had a full width at half max of 17 µm. The discrepancy in the lateral spot size from the estimated value of 6 µm was attributed to the 9 µm pixel size of the imaging camera that was used in the measurement.

4.5 Summary

A novel implementation of interference spectral and spatial transmission filters was proposed and demonstrated. Multiplexed spatial and spectral transmission profiles were obtained by patterning diffractive optical elements in defect layer of a photonic crystal transmission filter. Spectral and spatial transmission characteristics were studied by simulation and the experimental results match closely with the expected spatial and spectral transmission profiles. The number of discrete wavelengths transmitted was the same as the number levels in the case of the diffractive structure. Triangular wedges with wavelength dependent orientation were transmitted spatially. In the case of the analog lens structures a pseudo-continuous spectrum of wavelengths could be selected within the DBR stop band and a wavelength dependent spatial transmission profile was obtained. The demonstrated devices have applications in graded reflectivity mirrors for laser resonators, hyper spectral imaging, engineered illumination and pupil filtering applications.
While interference filters have been predominantly applied in the detector side of the imaging system, filters demonstrated in this work can be incorporated as a part of imaging system resulting in novel applications.
5 SPATIAL BRIGHTNESS ENHANCEMENT OF BROAD AREA DIODE LASERS

5.1 Introduction

The concept for lasers and masers were developed by the Nobel Prize winning work of C. H. Townes of the USA, and N. G. Basov & A. M. Prokhorov of the former Soviet Union in the late 1950s [78]. The world’s first laser was built by Theodore Maiman in 1960, a pulsed ruby device at the Hughes Research Labs [79]. Following advancements in semiconductor technology, work at General Electric, Lincoln labs and IBM led to the development of the world’s first semiconductor diode lasers in the fall of 1962 [80-83]. The field has since experienced tremendous research advancement and growth [84]. Today, semiconductor lasers are ubiquitous and can be found in several devices and applications. Infra-red semiconductor emitters are widely used as the sources in telecommunication applications, bar code readers, fingerprint scanners, compact disc players, cellular phones and data transfer applications. These applications use lasers with a low output power of a few milliwatts. High power lasers (>100 mW) with enhanced spatial brightness have emerging applications in machining of materials, tissue ablation and precise surgical procedures. The use of semiconductor lasers in such applications can lead to miniaturization of the system.

A well known method of increasing the power output of a semiconductor laser under continuous wave operation is to use a broad laser stripe to provide higher gain and avoid gain saturation and filamentation effects. As a result, the field distribution in the waveguide becomes multimode. In conjunction with the quantum well gain structures used to achieve a narrow gain spectrum, the output beam is highly astigmatic. This results in a poor beam quality reduced spatial brightness. Collimation and focusing of the astigmatic and multimode output beam
requires the use of expensive high numerical aperture lenses and is non-trivial. Increasing the output power of a diode laser with an equivalent increase in spatial brightness is challenging. Other methods have been explored to improve the output beam profile. The most promising approach to improving the beam quality of the broad stripe laser is to control the transverse field profile within the laser cavity by selective excitation of desired transverse modes of the laser cavity. This has been accomplished by using graded reflectivity mirrors which preferentially increase the round trip loss in the cavity. The improvement in beam quality is limited to low pumping conditions and the higher order transverse modes begin lasing at higher pumping conditions. Intra cavity diffractive elements with a phase profile that matches the phase of the desired transverse mode have also been introduced in the cavity to achieve desired output beam distributions. High power operation of vertical cavity surface emitting lasers has been demonstrated in this configuration. These techniques will be reviewed in greater detail in the following sections.

In this chapter, we describe a technique for spatial brightness enhancement of high power broad area laser diodes using external space variant grating based mirrors. The spectral wavelength stabilization of the diode laser was achieved by choosing the period of the space variant grating to match Littrow condition in a configuration coined space variant external dual wavelength reflector (e-DGR). Before the role of space variant laser mirrors in the spatial brightness enhancement is explored, the following sections will provide a brief overview of the techniques and methods employed to stabilize the operating wavelength of diode laser. This will be followed by a review of other techniques that have been used to improve the spatial brightness of the diode lasers.
5.1.1 Spectral Brightness Enhancement

Figure 5.1 shows a schematic of the gain and loss mechanisms in a laser cavity. The spectrally selective mirror provides the wavelength selective feedback for the light in the cavity by preferentially enhancing the loss for the undesired axial modes. The spacing and linewidth of axial modes in a laser cavity are a function of the cavity dimensions. The spectral filter has to be designed in conjunction with the cavity it defines to allow single longitudinal mode operation.

By controlling the phase and amplitude of the reflection from the spectral mirror, feedback desired transverse modes can be enhanced. This has been explored extensively in solid state lasers by using complementary reflectivity Gaussian mirrors for out coupling the light. The loss in out coupling efficiency is offset by the pseudo single mode laser operation and resulting beam quality. The coupling losses typically lack spectral dependence since they are related to divergent beams within the cavity, loss in coupling optics and the like. Space variant laser
mirrors have been used extensively for transverse mode control and beam quality enhancement in laser structures [85, 86]. The introduction of discontinuous phase elements in laser cavities for providing high gain for certain transverse modes while negatively perturbing others has been studied widely [87, 88].

Several methods have been employed to control the lasing spectrum while enhancing the maximum achievable output power. Narrow line width stabilized high power diode laser operation has been achieved using technologies such as Distributed Feedback (DFB) mirrors and Distributed Bragg Reflectors (DBR) [89]. The DBR laser is designed such that the lasing line width is controlled by the spectral reflection of the DBR mirror and is designed in conjunction with the cavity it defines to maintain a single lasing mode. The DBR mirrors are best suited for lasers with a small gain volume and the single volumetric lasing mode.

More recently the integrated Dual Grating Reflector (DGR) element [90] has been developed for the wavelength stabilization of broad stripe grating coupled surface emitting diode lasers. This element consists of two gratings one for converting guided radiation into free space radiation, and the second for providing wavelength selective feedback operating in Littrow condition. The diode laser in the absence of the wavelength selecting n-side grating outcouples the radiation from the backside of the device. This configuration is schematically illustrated in Figure 5.2(a). The diode laser was constructed in a single quantum well based graded index separately confined heterostructure (GRINSCH). The structure was electrically pumped to achieve photon generation within the quantum well. The single mode wave-guiding structure provides cross sectional confinement for the light generated. The transverse confinement was achieved by gain guiding. The radiation generated propagated towards the gratings placed at either end of the laser stripe. The reflection at the interface between the wave guiding region and
the grating region was designed to have low reflection. This was achieved by wet etching the structure to an etch stop. The plane dependent etching generated a profile that matched well with the mode structure of the light propagating within the waveguide. This also ensured optimal placement of the grating with respect to the wave guide. The period of this grating was detuned from the DBR condition and as a result the out coupling grating interacts with the radiation propagating as a guided wave within the GRINSCH waveguide and converts it to free space radiation. The period of the grating was chosen not to exceed the condition for total internal reflection at the back surface and allow light emission from the n-side of the device. Due to the grating dispersion, the individual wavelengths of the broad spectral radiation were angularly dispersed in space. To cut off the order diffracted into air, a high reflection coating was applied to reflect the radiation back through the substrate. The device was operated in a super luminescent LED mode.

Lasing wavelength selection was performed by placing an integrated grating operating in Littrow condition in the path of the angularly dispersed beam in one of the output arms of the GCSEL. This configuration is schematically illustrated in Figure 5.2(b). In this wavelength stabilization arm, the outcoupling grating period was reduced from the previous conditions to cut-off the orders into air and achieve high efficiency coupling into the substrate. This made the high-reflection coating on the wavelength locking side redundant as shown in Figure 5.2(b).
When the wavelength of light incident upon the n-side grating matched the Littrow condition, the light was redirected back along the incidence direction. The wavelength of stable operation could be described in terms of the out coupler period $d_{gc}$ and feedback grating period $d_f$ and the effective index of the grating region $n_{eff}$ by the equation,

$$\lambda_{SW} = \frac{2d_{gc}d_f}{2d_f - d_{gc}n_{eff}}$$  \hspace{1cm} (5.1)

The out-coupling grating recoupled the light back into the waveguide by principle of reversibility. The coating is still necessary on the outcoupling side since the grating period on this side was kept large enough not to exceed total internal reflection angle at the back interface and allow laser emission. High power narrow line width thermally stable operation was achieved since the lasing line width is controlled by a grating far removed from the active stripe region. Though the beam divergence was smaller than Fabry-Perot resonators, the beam was astigmatic as shown in Figure 5.2 [91]. Even though the grating offers a certain amount of lateral mode control as do the dimensions, single mode operation is not possible for large stripe widths. High efficiency, high power operation with improved beam quality is possible with better lateral mode control and mode shaping.
5.1.2 Spatial Brightness Enhancement

Figure 5.3: Schematic illustration of the spatial beam profile from a broad area Fabry Perot laser

Low beam quality is particularly acute in the case of a semiconductor gain medium. The typical structure of a Fabry-Perot broad stripe diode laser is shown in Figure. The fast axis of a diode laser results from an asymmetric waveguide. In order to reduce threshold current and improve the internal quantum efficiency, a quantum well structure is typically used as the gain medium. In the z-dimension the waveguide is on the order to 200 nm. Gain guiding is used for wave guiding in the other dimension and in order to achieve high power operation is made a few hundred times larger. Due to the small dimension of the diode in the direction of the fast axis a single transverse mode propagates in this direction. Thus, while the beam is highly divergent in this direction, it can be collimated to a diffraction limited spot by an aspheric lens with a high numerical aperture of NA. In the slow axis however, the beam is highly multimoded and therefore the slow axis beam quality is the major drawback of broad area diodes.

The beam quality of a diode is measured in terms of the deviation from a standard Gaussian beam. The metric that defines this deviation is called the $M^2$ factor. The factor is defined as,
$$M^2 = \frac{w_0 \theta}{w_\theta}$$  \hspace{1cm} 5.2

The Rayleigh range, beam waist and other beam parameters are modified by this factor according to,

$$w(z) = w_{oM} \sqrt{1 + \left( \frac{z \lambda M^2}{\pi w_{oM}^2} \right)^2}$$

$$w(z_R) = \sqrt{2} w_{oM}$$  \hspace{1cm} 5.3

$$z_R = \frac{\pi w_{oM}^2}{\lambda M^2}$$

$$b = 2z_R$$

It is important to note that the Rayleigh range decreases while the diffraction limited spot decreases. The factor is a measure of the number of higher order modes that exist in the beam. A first order Gaussian beam has a $M^2$ factor of 1.

Space variant gratings have been used to tailor the phase of the out coupled beam at each point in the out coupler to achieve collimation, focusing and beam splitting [92]. The schematic of these devices are shown in Figure 5.4.

The light that was generated in the gain medium (indicated by the gold stripe in figure) was outcoupled by grating structures whose period was detuned from the Bragg condition. The grating area was divided into 200 x 200 cells. A small but designed shift was introduced in the gratings cells with respect to one another. The magnitude and direction of this shift was location dependent and was performed to introduce a local phase shift of the outcoupled radiation. The phase of the entire beam can be tailored to provide focusing, collimation or any other desired optical function. The shift in the grating also produced a phase shift of the light reflected back into the waveguide and if this was not accounted for in the design procedure could result in
excessive scattering and poor beam quality [93]. Furthermore modification of the grating coupler required the need for complex electron beam patterning tools since low quality tools could result in stitching errors that would cause stray radiation and undesired phase shifts.

Figure 5.4: Schematic representation of multifunctional grating out couplers implemented in grating coupled surface emitting laser devices to achieve focusing, collimation or splitting of the beam.

Graded reflectivity mirrors have been realized from space variant grating structures and applied to beam quality enhancement of broad stripe Fabry-Perot lasers. A grating with variable depth as shown in Figure 5.5 was operated externally in Littrow configuration, to provide a space variant reflection. The efficiency of diffraction in the ‘-1’ order has a strong dependence upon the grating fill fraction and etch depth. As the grating depth was varied spatially, the local diffraction efficiency was a function of the grating depth encountered by the radiation. The spatial reflection was varied in a Gaussian profile from a maximum of 30% at the center of the grating to 10% at the edge. The space variant reflection resulted in excellent beam quality at low
pumping conditions \((I = 1.2I_{th})\). At higher pumping conditions, however, the higher order transverse modes attained threshold and the beam quality deteriorated rapidly.

A three mirror coupled cavity laser [94] system has also been employed for beam quality improvement by transverse mode selection. A schematic diagram of the setup is shown in Figure 5.6. The phase shaping functionality was applied to a single mirror in the structure. By designing the conjugate mirror profile to match a chosen higher order Gaussian mode profile the output beam profile was tailored to obtain flat-top and other complicated profiles. The field interaction with the gain profile was also significantly improved [94]. The central axial mode selecting element was designed to achieve single longitudinal mode operation of the cavity as shown in Figure 5.6. Using this technique, high power operation of VCSEL devices, previously unattainable, has also been achieved by using external cavity aspheric elements for lateral mode shaping forming an extended cavity [95].
5.2 Device Concept

The basic configuration of the grating coupled surface emitting laser with externally mounted Littrow grating developed in this work is shown in Figure 5.7 (a). The light generation and extraction was accomplished using a standard grating coupled surface emitting laser design. It consisted of a grating detuned from the Bragg condition with high reflection coatings to enable single side emission. The external dual grating reflector (e-DGR) consists of a p-side out coupler grating with a 270 nm period coupled with externally mounted gold coated silicon grating with desired period on the n-side. The out coupling grating period was designed to satisfy two conditions. First, the period was large enough to allow the angle of the first diffracted order to be smaller than the critical angle at the n-side of the device so that order was transmitted into air. The period was small enough to cut off any other higher diffracted orders. This grating transformed the incident spectrum into a wavelength dependent angular spectrum. The radiation passes through the antireflection coated n-side of the substrate and was then incident upon the silicon grating. When the angle and wavelength satisfy the Littrow condition the radiation was retro reflected back into the substrate. Thus, the period of the external feedback grating determines the lasing wavelength $\lambda_{SW}$, also denoted as the stabilization wavelength. The
feedback grating was flip-chip bonded on the n-side using a silicon spacer and a eutectic bond. This enabled a reversible and compact configuration to be realized. The radiation when incident upon the p-side grating was coupled back into the active waveguide region of the device. A HR coated 270-nm period grating on the other side of the gold contact on the p-side and an AR coated n-side were used to out-couple the laser radiation.

The rectangular dimensions of the wave guiding region and different number of modes existing in each dimension resulted in an astigmatic beam. The divergence of the emitted radiation parallel to the laser stripe (X-dimension) was smaller compared to a Fabry-Perot device since the grating out coupler provides highly directional beam. In this direction, the beam could be collimated efficiently using low numerical aperture optics. The GCSEL configuration, however, does not make any effective modifications to the beam divergence in conventional slow axis (Y-dimension). Different optical functions such as lenses for focusing and collimation of the diverging beam have been incorporated on the n-side for beam quality enhancement in this direction. Other optical elements such as blazed gratings for beam correction and grating structures for anti-reflection coatings and beam splitting have also been incorporated [90, 97, 98]. These structures do not provide an effective improvement in beam quality of the multimode beam. In this work, we used space variant gratings provide a variable reflection profile in this dimension as shown in Figure 5.2(b). The graded reflection was achieved by varying the duty cycle of the external feedback grating. These grating structures operate by increasing the loss experienced by selected transverse modes in the laser stripe.
In order to estimate the effect of the external resonator elements on the performance of the laser system as a whole, an understanding of the relationships between the basic parameters is essential. The effective reflectance of the entire external mirror arm in a standard configuration can be estimated from the individual reflectance provided by the cavity elements through which the light exits the semiconductor gain region which is typically broadband and the spectrally selective reflectivity of the external cavity optics. The effective reflectance of a single arm of the external cavity laser diode can be represented as[99-101]

\[
r_{\text{eff}} = \frac{r_f + r_{\text{ext}} \exp(i2\pi v \tau_{\text{ext}})}{1 + r_f r_{\text{ext}} \exp(i2\pi v \tau_{\text{ext}})}
\]
Here, \( r_{\text{eff}} \) is the effective reflectivity of the radiation coupled back into the laser cavity from the external mirror arm, \( r_f \) is the reflectivity of the mirror on the outcoupler side, \( r_{\text{ext}} \) is the reflectivity of the grating.

Figure 5.8: The grating coupled surface emitting laser (GCSEL) is well suited for our application. The loss in effective reflection from the external mirror due to the graded reflectivity does not result in significant drop in the output efficiency of the diode laser.

The gain and loss mechanisms of the external cavity laser contribute to the threshold current. When the round trip gain, which is dependent upon the injection current in an electrically pumped laser diode, and the round trip loss contributed to by the loss of light through the mirrors due to out coupling, and scattering are equal the laser operates at threshold condition. The mirror loss term can be represented as

\[
\alpha_{\text{mir}} = \frac{1}{L_{\text{int}}} \ln \left( \frac{1}{r_{\text{eff}}(\lambda) r_{\text{eff}}(\lambda)} \right)
\]  

The gain coefficient per unit length of the semiconductor gain section is

\[
g(I, \lambda) = \gamma (I - I_{\text{tr}}(\lambda))
\]  

where \( I \) represents the pump current, \( I_{\text{tr}} \) is the transparency current and \( \gamma \) is a constant.
Thus the threshold current can be derived as the pump condition at which the total gain and loss terms equal one another. This can be written analytically as,

\[ I_{th} = \frac{1}{\gamma} \left( \alpha_{int} + \alpha_{mir} \right) + I_{tr} \quad 5.6 \]

where \( \alpha_{int} \) is the internal propagation in the passive sections of the gain region and semiconductor crystal.

The output power above threshold from the laser configuration can be theoretically estimated by considering the electron to photon conversion efficiency and the fractional loss due to the mirror out-coupling and scattering. This can be written as follows

\[ P_{out} = \frac{h \nu}{q} \frac{\alpha_{mir}}{\alpha_{mir} + \alpha_{int}} (I - I_{th}) \quad 5.7 \]

The outcoupling efficiency as a function of external mirror reflectivity is shown in Figure 5.8 for different values of the reflectivity from the outcoupling grating region. As this value increases, lower values of the reflection from the external mirror arm result in a significant drop in output efficiency. The outcoupling grating region has a low reflectivity due to the wet etching process used to create the mode matching surface and is on the order 0.1%. Thus, the loss in effective reflection from the graded reflectivity mirror does not impact the performance of the diode laser significantly. This is an important advantage of the space variant external dual grating reflector design since significant losses in output efficiency compared to a diode laser locked with a Littrow with no space variant reflection will mitigate the performance achieved from this configuration.
5.3 Feedback Grating Reflection Profile Design

An analytical expression was derived for the stabilization wavelength of the structure by considering the grating equation for the two gratings. The out coupling angle of the grating from the light emitting diode is related to the wavelength of emission as,

\[ n_1 \sin \theta_1 + n_{eff} = \frac{\lambda}{d_{gc}} \]  

(5.8)

Here, \( n_1 \) is the index of the GaAs, \( \theta_1 \) is the exiting angle from the grating, \( \lambda \) is the corresponding wavelength and \( n_{eff} \) is the effective index of the grating parameter. When the light exits the GaAs, the angle in air is given by,

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]  

(5.9)

Here, \( n_2 \) is the index of air or substrate and \( \theta_2 \) is the angle in air or substrate.

The wavelength at littrow operation is related to the incidence angle by the relation

\[ 2n_2 \sin \theta_2 = \frac{\lambda}{d_f} \]  

(5.10)

Here, the \( d_f \) is the period of the littrow grating. Solving for the stabilization wavelength we get,

\[ \lambda = \frac{2d_{gc}d_f}{2d_f - d_{gc}n_{eff}} \]  

(5.11)

Substituting the values for effective index of the grating to be 3.24, out-coupling grating period to be 270-nm, feedback grating period to be 1.25-µm, 1.35-µm or 1.45-µm in (4) we obtain the stabilization wavelength to be 980.7-nm, 972-nm, 964.6-nm for the feedback grating periods respectively.

The efficiency of retro reflection under littrow condition was modeled using a finite difference frequency domain (FDFD) algorithm as a function of duty cycle and grating depth.
The reflection profile varies smoothly with grating fill fraction for larger etch depths as shown. The simulated structure was assumed to have a layer of gold 80-nm thick coated on it. The power reflected back into the first order is simulated as a function of duty cycle and etch depth. In the case of standard littrow gratings, a shorter etch depth with a fill fraction of close to 0.3 provides excellent performance with high reflectivity. It is apparent that a graded reflectivity profile can be obtained from a Littrow grating by changing the grating depth or the grating fill fraction across the device aperture. Graded reflectivity mirrors realized by varying the fill fraction across the feedback aperture were designed by setting the local fill fraction according to the reflectivity profile that was desired. For the fabrication of variable reflectivity mirrors, the grating duty cycle will be varied according to best performance for desired grating period. At larger fill fractions, the reflection profile deteriorates. This is because the incident field encounters large portions of metal and this performs more as a specular reflector instead of a metal grating structure. Table 4 summarizes the target grating parameters. The period of the gratings is close to the resolution limit of the stepper which is 1.15 µm since locking wavelength close to 975 nm is desired.

![Figure 5.9: (a) The reflectivity as a function of grating depth for a 50% duty cycle and different grating periods is shown. (b) The reflectivity as a function of fill fraction for an etch depth of 1.6µm for different grating periods is shown.](image-url)
Table 5-1: Grating Specifications for optimal performance

<table>
<thead>
<tr>
<th>Period (µm)</th>
<th>Duty Cycle</th>
<th>Etch Depth (µm)</th>
<th>Locking Wavelength (nm)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>0.59</td>
<td>1.25</td>
<td>976.2</td>
</tr>
<tr>
<td>1.35</td>
<td>0.57</td>
<td>1.25</td>
<td>972</td>
</tr>
<tr>
<td>1.4</td>
<td>0.55</td>
<td>1.25</td>
<td>968.2</td>
</tr>
<tr>
<td>1.45</td>
<td>0.53</td>
<td>1.25</td>
<td>964.6</td>
</tr>
</tbody>
</table>

The 1.35µm period Littrow grating was chosen to provide the desired spectral locking wavelength of 972.4nm. Parametric curves were obtained as shown in Figure 5.9. In order to maximize the diffraction efficiency in the first order at a fill fraction of 0.3, the etch depth of the devices were chosen to be 1.6 µm.

The reflectivity profile required to generate a variation in diffraction efficiency was calculated from the numerical plots shown in Figure 5.9(b). The stripe width was chosen to be 400 µm and the diffraction of the wave upon propagation to the littrow was taken into consideration. A Gaussian reflectivity profile was targeted from the littrow grating. The required fill fraction plots as a function of distance from the center of optical axis are shown in Figure 5.10. While the fill fraction variation has been estimated from the numerical model, experimental characterization of the grating reflectivity as a function of duty cycle and depth is necessary to get an experimental reference points to validate the model. By using exposure matrices, the gratings with different fill fractions can be fabricated on a single wafer. Since the duty cycle variation is largely linear, phase masks that produce a linear intensity ramp can be used to
achieve the fill fraction variation. It is noted that the variation in fill fraction will need to be produced perpendicular to the grating grooves for the concept to be implemented.

Figure 5.10: Plot of grating fill fraction required to achieve the required reflectivity variation.

## 5.4 Fabrication of Space Variant Gratings

A uniform coating of metal is vital to achieve high reflectivity. The metal coating process was tested on the sputter coater. Since the tool uses an DC magnetron plasma to bombard and dislodge material from the target and deposit on the surface of the wafer, a conformal metal coating was expected. Gratings of 2 µm period were patterned on a silicon wafer and etched using the BOSCH process to a depth of 1.41 µm. The photoresist was stripped and the wafer was cleaned thoroughly in piranha and exposed to oxygen plasma. In the sputter tool, a wetting layer of Titanium (Ti) ~ 4nm thick was deposited using RF plasma followed by a 80 nm thick layer of Gold (Au). Good quality deposition was obtained. The samples were cleaved parallel to the grating vector and inspected under the SEM. Figure 5.11 shows the images of the silicon gratings coated with gold. A uniform coating of metal was obtained on the grating surfaces. The deposition process lasted 16 min and deposited a total of 67 nm all around the grating groove at a
rate of ~4.2 nm/min. High quality coating were obtained. Other wetting layers such as chrome can also be used since targets are available for it. The process represents a promising way to achieve the required metal coverage to maximize the grating efficiency.

![SEM images of Ti/Au coating on silicon grating](image)

Figure 5.11: SEM images of a coating of Ti/Au on a silicon grating. Uniform coating of gold was achieved on the grating. The ridges seem on the grating sidewalls are a result of the pulsed etching of the BOSCH process.

The fabrication of the p-side contacts, and n-side contacts were accomplished by contact lithography followed by metal deposition and lift off. The out-coupling grating was patterned using electron beam lithography and GaAs etching. The process steps and methodology is described in detail elsewhere [98, 103]. The feedback grating was patterned on a g-line, GCA 6300 stepper tool. The theoretical resolution limit of the stepper estimated from the
manufacturer defined physical parameters was 1.15 µm. In order to pattern the gratings that are close to the resolution limit and control their duty cycle a two step exposure technique was used. The method partially forms the grating latent image in the first exposure and is followed by an open exposure that saturates the exposure in the grating grooves [104, 105]. The method results in high quality grating structures that were subsequently transferred to the silicon substrate by dry etching using a BOSCH process [106].

5.5 Results and Discussion

Scanning Electron microscope images of the fabricated structures are shown in Figure 5.12. Two sets of feedback gratings were fabricated. One set of gratings had different periods to achieve and demonstrate multiple locking wavelengths. The other set of gratings had variable fill fractions to provide space variant reflection to the first order modes. The gratings were reversibly mounted on the n-side of the processed laser dies by flip chip technology using a eutectic bond. The alignment precision was within 10 µm. The gratings and the spacer were offset from the center of the outcoupling grating to account for the angle of the diffracted order and its refraction into air. The scheme offers several important advantages compared to fully integrated devices. The wavelength selecting element can be easily replaced post fabrication to change the operating wavelength within the gain spectrum. Gratings of different periodicities may be used in an array to achieve multi wavelength high power diode laser arrays.
Figure 5.12: (a) Top view of the fabricated variable fill fraction gratings. An analog intensity profile that generates a pair of cylindrical lenses was used. (Inset) Magnified images of the grating at different spatial locations. The rectangles indicate the region which has been magnified. (b) The plot of fill fraction variation from the edge to the center of the variable duty cycle grating structures. The minimum grating duty cycle was 0.24 and the maximum was 0.3. (c) Simulated plot of reflectivity variation as a function fill fraction for a grating period of 1.35 µm and etch depth of 1.6 µm. For the fabricated structures, the reflectivity varies between 92.48% at the center of the laser stripe which is 200 µm wide down to 73% at the edge of the beam that interacts with the littrow gratings.

The stabilized spectral lasing wavelength, light output as a function of pump current under pulse pumping and spatial beam profiles of externally locked grating coupled surface emitting
laser devices were characterized. The performance metrics were estimated under two conditions. First, uniform (unmodulated) gratings were used to lock GCSEL devices with a 200µm stripe. Uniform gratings with periods of 1.25, 1.32 and 1.42µm with no fill fraction variation were placed externally at a distance of ~450µm. The pump current was provided using a pulse driver with a repetition rate of 0.5µsec. Figure 5.13 shows the lasing spectra and efficiency obtained from the straight stripe gratings with different periods. Three lasing wavelengths were achieved by using feedback gratings of different periods as shown in figure. A narrow lasing linewidth of 0.2 nm was realized for all wavelengths. Slope efficiencies of 0.82 W/A were achieved which was comparable to those achieved on the integrated DGR devices [90]. There was a variation in the efficiency with wavelength that was attributed to the wavelength dependence of gain of the quantum well structure.

![Figure 5.13](image)

Figure 5.13: (a) Experimentally measured lasing spectra for locking using straight stripe gratings are shown. The stabilization wavelengths were 966.2nm, 974nm and 979.5 nm for feedback grating periods of 1.42 µm, 1.32 µm and 1.25 µm. (b) The output power as a function of pump current for pulse operation was measured to be 0.82 W/A which was comparable to the GCSEL devices with integrated dual grating reflectors.

The same performance metrics were estimated when the uniform and space variant gratings were used to lock 400µm stripe devices. The beam quality enhancement achieved using the variable fill fraction gratings was also estimated on these devices. The gratings were placed ~ 2
mm away from the n-side of the GCSEL and aligned. Using a beam divergence angle of 10° (measured on DGR devices which will have divergence similar to external littrow devices) from the n-side of the device, it was estimated that the beam would interact with 420 µm of the grating structures when they are placed at a distance of 2 mm. A camera was used to determine the position of beam interaction with the Littrow structures.

The measured spectral characteristics and efficiency on 400 µm stripe devices locked with uniform gratings are shown in Figure 5.14 (a) and (b). The spectral linewidth was measured to be 0.25 nm and the efficiency was measured to be 0.3 W/A. The efficiency of the laser structures locked using space variant gratings was measured to 0.22 W/A. The 20% drop in efficiency can be related to the highly multi-mode beam emitted from the laser. In addition, the reflectivity of the low reflection surface was measured to 0.011 which corresponds to a large drop in efficiency when the feedback coupling efficiency from the external element is low. Due to the diffraction losses associated with the multimode beam, the coupling efficiency of back into the laser cavity from the external element was estimated to be 30%. This was significantly lower than the feedback coupling measured on the 200µm stripe devices where the external grating was placed closer to the laser stripe and the number of lasing modes was greatly reduced. The large stripe width is a reason for the lower efficiencies since it is comparable to the stripe length and under this condition lateral lasing leads to higher losses and reduced efficiency of operation.

Despite the lower measured efficiency, these devices are ideal to demonstrate the spatial brightness enhancement obtained by locking using the space variant grating structures. The spatial variation in duty cycle occurs over ~350 µm and as a result using 200 µm stripe width devices does provide the expected beam quality enhancement. Phase masks that can be used to provide the variation over smaller widths were unavailable. Hence space variant gratings were
used to lock GCSEL devices with 400µm stripe widths. The beam profiles were imaged on to a CCD camera placed at a distance of 53 mm from the device. The far-field profiles for devices locked using the space variant gratings operated in Littrow condition are shown in Figure 5.14. Care was taken so as to fill only one of the two variable fill fraction arms of the grating by observing the area of incidence using a high zoom microscope. The improvement in beam quality is immediately visible. The beam profiles for pumping at 5 times the threshold current of 1A are shown in Figure 5.14 (c).

![Graphs showing efficiency, spectral linewidth and beam profile](image)

Figure 5.14: Efficiency, spectral linewidth and Beam Profile of the broad stripe diode lasers locked using external gratings in Littrow condition. (a) Comparison of the efficiency measured using uniform and space variant external gratings. (b) The spectral linewidth was 0.25nm and was comparable to those achieved from the integrated DGR devices. Devices locked using space variant and uniform gratings at a pumping condition of (c) 5A and (d) 8A. The repetition rate was 10 KHz for each.
Excellent beam quality was achieved with no collimating optics. The beam divergence angle was estimated from the measured full width half max (FWHM) of the beams. The beam divergence was comparable to the slow axis divergence and was 1.41°. The corresponding output power at this pumping condition was 0.7W. The spatial brightness enhancement was estimated as a ratio of the brightness of the beam obtained by locking using the space variant gratings to the brightness obtained by locking the devices using uniform gratings as,

\[
B_{\text{enhancement}} = \frac{B_V}{B_U} = \frac{P_V}{P_U} \frac{\theta_{Uy}}{\theta_{Vy}} = 4.6
\]

Here, \(B_V, P_V\) and \(\theta_V\) correspond to the brightness, power and full divergence angle from space variant gratings and \(B_U, P_U\) and \(\theta_U\) are the same parameters obtained from the uniform gratings. The brightness was improved 4.6 times at high pumping conditions and high power operation. This is significantly larger than previously reported values. As the pumping current was increased, the higher order modes achieve threshold lasing condition and the beam divergence increases to a full angle of 6.4°. At this condition, the effect of the spatial reflectivity variation was minimal and the higher order transverse modes achieve lasing. The slow axis beam divergence was 1.0°. The improvement in brightness due to the space variant gratings was calculated in this condition as,

\[
B_{\text{enhancement}} = \frac{B_V}{B_U} = \frac{P_V}{P_U} \frac{\theta_{Uy}}{\theta_{Vy}} = 1.48
\]

Though the enhancement in brightness reduced to a factor of 2, this is still significant in several applications since the improved beam quality was obtained at high power operation. As was previously stated, the spectral linewidth remained constant at .25nm throughout the pumping range. Thus the space variant grating efficiently performs the two functions of improving the
spatial and the spectral brightness of the broad area diode laser device. The 10% loss in efficiency can be offset by the improvement in beam quality obtained at high pumping conditions. These compact devices suitable for high power operation with excellent beam quality have applications in high efficiency second harmonic generation and laser machining.

5.6 Summary

The spatial and spectral brightness enhancement of broad area laser (BAL) diodes was demonstrated using graded reflectivity grating structures. Previously published results used a variable depth grating with 50% fill fraction to provide a graded reflection. The beam quality enhancement was limited to low pump currents \(I = 1.2 I_{th}\). In our work, the graded reflection was achieved by spatial modulation of the fill fraction for a designed grating depth. The near-field and far-field profiles of the laser as a result of the graded reflectivity mirror were studied. The near-field has a low intensity at the center of the stripe and the corresponding far-field has a reduced spatial extent at high pumping conditions. The beam quality factor was improved by a factor of five (5X). The laser efficiency showed a 20% drop in efficiency compared to the efficiency obtained when a standard Littrow grating was used to lock the wavelength. However, the spatial brightness was enhanced by two times as compared to the standard configuration at high pumping conditions \(I = 8I_{th}\).
6 SPACE VARIANT GUIDED MODE RESONANCE MIRRORS

6.1 Introduction

Graded reflectivity mirrors have been widely used in laser cavities for mode control and output beam shaping [107]. These mirrors operate by preferentially increasing the loss for selected transverse laser cavity modes. Convex Gaussian reflectivity profile mirrors have been demonstrated to improve the far-field beam profile [108, 109]. The operation of an resonator with a Gaussian spatial reflectivity mirror increases the total power output [110]. The beam quality enhancement is particularly attractive for high power lasers. The larger waveguides required to achieve higher gain result in a multimode output beam. A graded reflectivity mirror in conjunction with an intra-cavity phase element has been used to demonstrate near fundamental mode operation of the laser cavity [111]. More recently, it has been shown that quasi Gaussian output beam can be achieved in a resonator configuration by matching the highs and lows of the space variant mirror reflection to the field modulation. This method exploits the self imaging properties of a multimode waveguide of discrete length placed between two mirrors in conjunction with the spatial reflectance profiles to control modal discrimination [112]. Multimode interference (MMI) effects have been used for frequency dependent shaping of the transmitted beam by adjusting the waveguide length to coincide with the predicted location of the desired beam shape within the waveguide [113]. Space variant frequency dependent reflection surfaces have also been implemented using frustrated total internal reflection [114].

Techniques for realizing graded reflectivity mirrors are limited and depend on complicated deposition techniques [115, 116]. These mirrors provide a phase shift to the reflected and transmitted beams which is undesirable in certain cases. Any non-uniformity in the films can lead to performance deviations from design. Apodized grating based mirrors have been explored
to generate space variant reflection. They include variable depth gratings operated in littrow configuration and variable duty cycle amplitude gratings that scatter the higher diffracted orders outside of the cavity [111, 117]. However, these structures have larger associated losses due to scattering and absorption.

Figure 6.1: A space variant GMR filter for beam shaping. Different wavelengths incident on the filter will have different beam shapes that vary with wavelength.

In this work, we propose and demonstrate all dielectric guided mode resonance (GMR) filters with space variant functionality to provide frequency dependent spatial reflection and transmission. Figure 6.1 shows the conceptual operation of the proposed device. Guided mode resonance filters have been widely used as narrow band spectral filters [33]. In typical configuration, such filters are constructed by placing a sub-wavelength grating in contact with a waveguiding layer. At the resonance wavelength, the grating couples the external waves into guided modes within the slab. The grating also out couples the guided radiation to produce sharp transmission and reflection responses around the resonance. The resonant condition is a function of the grating lattice structure, optical thickness, period, duty cycle and the optical thickness of the guiding layer [118]. The graded reflection profile can be obtained from a free space GMR filter by spatially varying the duty cycle of the unit-cell phase function across the device aperture.
The duty cycle variation induces localized changes in the frequency-dependent coupling conditions across the device and this effect can be exploited to generate graded reflection profiles from the filter. A standard GMR filter was recently applied as a feedback element in a fiber laser resonator [119]. The ability to obtain frequency dependent reflection from these filters is attractive for laser applications [114].

6.2 Device Concept

![Figure 6.2](image)

Figure 6.2: (a) Schematic of a Guided Mode Resonance Filter (b) Spectral Reflection as a function of hole diameter in the grating region (lighter regions represent higher reflection)

The structure of our GMR filter is schematically illustrated in Figure 6.2(a). A fused silica substrate was deposited with 230nm thick plasma enhanced chemical vapor deposition (PECVD) grown silicon nitride (Si₃N₄) and silicon oxide (SiOₓ) layers. A grating with a lattice constant of 1.15µm was lithographically patterned and dry etched into the low index oxide layer. The spectral response of a GMR structure of infinite spatial extent under plane wave illumination was simulated using rigorous coupled-wave analysis (RCWA), as a function of the hexagonal unit-cell feature diameter ($d$). The results are shown in Figure 6.2(b) [120]. As the diameter of the holes in the grating layer increases, the effective index of the grating layer decreased which
changed the coupling condition. For small variations in the feature size, the change of the
resonance location is approximately linear, and the linewidth remains unchanged. Excellent side
lobe suppression ratios were achieved as well as high peak reflection on resonance.

The intensity profile of the reflected and transmitted beams can be controlled using a GMR
by detuning its out coupling through the fill fraction across the optical element. The beam
incident upon the space variant element has a Gaussian intensity distribution ($P_{\text{inc}}$) which can be
represented as,

$$
P_{\text{inc}} = A_0 \exp \left( -2 \left( \frac{r}{w} \right)^2 \right); \quad r^2 = x^2 + y^2
$$

(6.1)

Here, $A_0$ is a constant and $w$ is the beam waist. The reflection intensity in the filter varied as
a function of radial location since the fill fraction was varied radially. Assuming that the area of
the space variant grating is larger than the beam and ignoring the asymmetry in the line shape for
simplicity, the reflected beam profile $R(r)$ as a function of the radial location from the center of
fill fraction variation follows a Lorentzian line shape and can be represented as,

$$
R(r) = \frac{1}{\pi} \left[ \frac{ff_{\Gamma} / 2}{(ff - ff_\lambda)^2 + (ff_{\Gamma} / 2)^2} \right] + A_{FP}(\lambda)
$$

(6.2)

where $ff = f(r); \; 0 \leq r \leq \rho$

(6.3)

where $ff$ is the local fill fraction as function of radial location from the center of the beam.
The function $ff$ is fixed once the space variant GMR is fabricated. $ff_\lambda$ is the fill fraction
concerning the reflection peak for a particular wavelength, $ff_{\Gamma}$ is the full width half max of
the Lorentzian representing the power reflected as a function of fill fraction, $A_{FP}(\lambda)$ is a term that
describes the reflection due to thin Fabry-Perot effects and $\rho$ is the radius of the beam. Various
wavelengths will encounter different spatial reflection profiles depending upon the range of feature sizes that are fabricated on the space-variant filter.

The reflected beam profiles can be represented as,

\[ P_{ref}(r) = P_{inc} \cdot R(r) \]  \hspace{1cm} (6.4)

A comparison of the analytical and RCWA determined power reflection curves is shown in Figure 6.3. The deviation of the analytical curves from the rigorously calculated values is due to the asymmetric line shape is of the guided mode resonance. The line shape can be made symmetric by appropriate design of the grating and wave guiding layer thickness to match the antireflection condition for the substrate [118, 121]. These analytical equations can be to study the effect between the range of fill fraction variation and their effect on the device performance. As shown in Figure 6.2(b), a wider spectral resonance provides a wider full width half maximum (FWHM) for the reflected power vs. feature size at an single wavelength of illumination. The asymmetry in the GMR design causes the line shape to deviate from the analytical prediction.
However, the equations predict the overall form of the curve relatively well. They can thus be used to analyze the effect of a few parameters on the device performance.

![Graph](image)

Figure 6.4: Comparison of the reflection profiles for a FMHM of (a) 20 nm and (b) 50 nm. For the reflection profile to exhibit no strong spatial nulls and provide a uniform reflectivity variation, the fill fraction variation that was fabricated on the wafer was kept within the full width half max of the power reflection vs. feature size curve.

The FWHM of the spectral reflection line shape (which in turn controls the spatial line shape) and the range of fill fraction variation affect the space-variant reflection profile. For a constant fill fraction, the reflection profiles below resonance, at resonance and above ‘spatial’ resonance are shown in Figure 6.4. The spectral location of the ‘spatial’ resonance corresponds to the spectral peak produced by a standard GMR (no fill fraction variation) that has a feature size the same as the feature size in the center of space variant GMR. The curves show the reflection obtained for different FWHM and constant fill fraction variation range. The device was designed to provide a uniform variation in reflection. Thus, the fill fraction variation was help within the FWHM of the power reflection vs. feature size curve. In the case of the GMR design used in this work, the maximum variation in patterned feature size across the beam was 100 nm since the FWHM was 110 nm.
The transmission profiles for an incident Gaussian beam passing through the space variant guided mode filter element can be calculated using Equation 6.4. The GMRF with a wide spectral resonance was chosen to provide uniform power reflectance across the beam. The corresponding FWHM of the power reflection as a function of feature size was 110 nm. For an ideal GMR, with a peak reflection of 100%, drastic changes in the transmission are obtained. In addition, spatial nulls are also observed. The peak reflection for a GMR of finite dimensions and the Gaussian beam illumination is less than 100%. The transmitted beam profiles for a non-
ideal GMR are shown in Figure 6.5 (c) and (d). The fill fraction can be varied in a designed manner across the beam using the process described in Chapter 3.

The transmission and reflection beam profiles, resulting from an incident plane wave with Gaussian beam profile, were a function of the type of duty cycle variation across the device. The transmitted and reflected beam profiles, correspond to a hole feature size that increases linearly from the center of the GMR device as a function of the radial location outward: $d = f(r + c)$. The linear variation in duty cycle provides different beam profiles below the nominal resonance (1549.3nm), at the nominal resonance (1550.7nm) and, above resonance (1552.8nm). The nominal resonant wavelength for the space variant GMR, corresponds to the spectral location of the peak obtained from an unmodulated GMR, with a duty cycle that is the same as those found at the center of the space variant GMR. Below resonance, a quasi-flat top transmission profile was obtained since the spatial reflection had a central peak. As the illuminating wavelength approached the spectral nominal resonance peak (1550.7nm), corresponding to the feature size at the center of the space variant element, the transmission profile has a central null. This was because the beam incident on the center of the GMR encounters a large reflection. The spatial width of the null was controlled by the FWHM of the GMRF spatial reflectivity profile. Above resonance, the inner rings of the space variant GMR transmit while the outer rings reflect. As the illumination wavelength was moved further away from the spatial resonance, the spatial width of the transmission null increased. The transmitted and reflected beam profiles, for a hole feature size width a quadratic dependence on the radial location ($d = f(x^2 + c)$). In transmission, apodized Gaussian beam profiles of different widths were obtained below and above the nominal resonance. At resonance, a flat top profile with a reduced aspect ratio was expected. These
profiles were broadened in reflection. The space variant GMR mirror thus provides frequency dependent beam profiles that depend directly on the function of the duty cycle variation.

The local reflectivity as a function of fill fraction for single wavelength of illumination calculated using coupled wave analysis (RCWA) is shown in Figure 6.6(a). A spatially variant GMR was designed by setting the local fill fraction according to this data so as to locally define the out coupled light intensity. The asymmetry of the line shape was due to the asymmetric waveguide used in the GMR. The spectral reflection from such a device consisted of a broader linewidth as shown in Figure 6.6(b). This was a result of the degraded resonance that resulted due the multiple fill fractions illuminated. The spectral linewidth from a GMRF with constant fill fraction was ~ 3nm for the design. When the fill fraction was varied from 0.43 to 0.35 across the optical element the reflection linewidth was expected to increase to ~ 7nm.

![Figure 6.6](image)

Figure 6.6: (a) The reflection profile as a function of feature size for different illumination wavelengths. (b) The simulated spectral reflection from the guided mode resonance filters with variable fill fractions is shown. The spectral reflection from the element is expected to have a wider linewidth due to the multiple fill fractions illuminated by the beam.

### 6.3 Graded Reflectivity Mirror Fabrication

Several methods for varying the fill fraction as a function of spatial location have been demonstrated for different applications. Among them electron beam lithography is a popular
technique since it can achieve smooth variations in fill fraction and fast local variations. A novel technique that uses the linear regime of the photoresist response curve to add binary and analog intensity profiles was used to achieve uniform smooth variations in grating fill fraction and fast local variations with high patterning fidelity across the element [105]. This technique will be described briefly.

The contrast curve of a typical positive photoresist to exposure dose can be roughly divided into three parts. In the first region, below its threshold, low exposure levels produce no significant chemical change in the photoresist. In the second region, above threshold, solubility of the photoresist as a function of moderate dose is approximately linear. The linear dependence of photoresist solubility has been previously exploited to ‘add’ the masking patterns in the photoresist [122]. The third region, which is beyond the linear part of the curve, is saturation where the photoresist is completely bleached and further exposure produces negligible change in solubility, or height of formed structures. The process used to create space variant gratings is schematically represented in Figure 6.7: (a) Aerial image intensity at the wafer plane of a lithographic stepper tool from a hexagonal grating cell when ‘added’ in resist to (b) the aerial image intensity from a phase only mask results in (c) a grating with space variant fill fraction. The local fill fraction is a function of the local dose. The fill fraction at the center of the unit space variant grating cell is the largest and decreases radially in concentric circles across the element. In the aerial intensity images, the lighter regions represent higher intensity.

The latent image of the desired binary grating function was first created using an exposure that was very close to saturation dose. Figure 6.7 (a) shows the aerial image intensity that was obtained at the wafer plane of the GCA g-line stepper tool used in this work. Since the period of the grating was very close to the resolution of the stepper tool, a multiple exposure technique
was used to fabricate the grating structures with a period of 1.15µm [123]. Analog intensity profiles generated from phase only masks that modulate the spatial intensity profile at the wafer plane were subsequently overlaid on the initial grating exposure prior to photoresist development. The phase masking technique was originally developed to create surface relief micro-optical elements and structures [48]. The spatial dose or energy profile \( E(r) \) for the exposure can be defined in terms of the grating and overlay exposure intensity \( I_0 \) and \( I(r) \) and time \( t_g \) and \( t_e \) respectively as,

\[
E(r) = I_0 t_g + I(r) t_e; \text{ and } t_e < t_{th}
\]

where, \( I(r) = I_1 + c_2 r^2 \); \hspace{1cm} (6.5)

\[
\text{Here, } c_2 \text{ is a constant controlled by the spatial intensity profile encoded in the phase only mask and } I_1 \text{ is the exposure at the point of least intensity, typically very close to zero. When the exposure focus was optimal, the change in critical dimension with exposure dose was approximately linear. By changing } t_e, \text{ the maximum and minimum fill fraction obtained across the element can be effectively controlled. The initial point of the fill fraction variation was controlled by the initial grating exposure time and the lowest point of the space-variant exposure intensity. It was imperative to maintain the overlay exposure time below the threshold exposure } (t_e < t_{th}) \text{ since once this condition was violated the overlay exposure resulted in thickness modulation of the photoresist.}

The total exposure was tailored to make sure that the resist was completely exposed at the position of least exposure. The local fill fraction of the patterned features was a function to the amount of the local dose received as a sum result of the uniform grating exposure and the space varying intensity profile of the overlay exposure. Decoupling the grating latent image formation and the spatial line width modulation steps facilitated the designed fill fraction variation to be
reliably achieved. The largest achievable fill fraction was limited by the smallest dose that could be provided to the photoresist to form grating structures upon development. At upper limit, when the overlay exposure dose was beyond the threshold of the photoresist, the adjacent features overlapped, resulting in development of the entire patterned area. Other techniques, such as gray scale and half tone masking, which provide space variant exposure intensity at the wafer plane, can be used in the overlay exposure.

Figure 6.7: (a) Aerial image intensity at the wafer plane of a lithographic stepper tool from a hexagonal grating cell when ‘added’ in resist to (b) the aerial image intensity from a phase only mask results in (c) a grating with space variant fill fraction. The local fill fraction is a function of the local dose. The fill fraction at the center of the unit space variant grating cell is the largest and decreases radially in concentric circles across the element. In the aerial intensity images, the lighter regions represent higher intensity.

In order to study the actual variation of fill fraction as a function of exposure dose, the grating pattern was partially exposed and overlaid with blank exposures of varying intensity. The fill fraction variation was measured for each exposure and plotted giving the modified dose curve. The variation in feature size with dose can be described according to Equation 3.3 as,

\[ E_x = E_N \left( \frac{1}{I_x} \right)^\gamma \]

Here, \( E_N \) is the energy required for the photoresist to be cleared for exposure through a mask less open aperture, \( E_x \) is the optimum energy of exposure for a given pattern size, \( I_x \) is the normalized image intensity for a given pattern and \( \gamma \) is a process parameter that relates the
change in development rate function for unit change in exposure energy. The value of $\gamma$ for our exposure parameters is 0.6 as obtained from the curve in Figure 6.8 (a).

Figure 6.8: (a) Patterned feature size variation as a function of deviation from the optimal dose. The optimal dose is the dose required to size the features according to the mask design.

A fused silica substrate was first deposited with a 230nm thick silicon nitride layer followed by a 230nm thick silicon oxide layer in a Surface Technology Systems (STS) PECVD chamber. The wafer was removed from the growth chamber and positive tone Shipley 1805 photoresist was spin coated to a thickness of 400nm. A binary hexagonal grating pattern was exposed in the photoresist using the pattern-shifting multiple exposure technique. Phase only masks that form the desired analog intensity profiles were used for the overlay. The patterns were developed resulting in binary gratings in a hexagonal lattice with uniformly varying fill fractions. The schematic of the space variant grating obtained using this novel technique post development is shown in Figure 6.7(c). The largest fill fractions and smallest holes are found at the center of each lens in the array and increases radially towards the edge of each lens.
On the same wafer, binary grating structures were patterned without fill fraction variation in order to baseline the process and test the performance of the filter in the absence of fill fraction variation. The gratings were transferred into the 230nm thick silicon oxide layer using CHF$_3$/O$_2$ plasma in a Unaxis Versaline etcher. The photoresist was stripped in a solution of boiling sulfuric acid and hydrogen peroxide and rinsed in water and blow dried using nitrogen subsequently.

### 6.4 Results and Discussion

SEM images of the fabricated gratings without fill fraction variation are shown in Figure 6.9(a). The inset shows a close up of one unit cell of the hexagonal grating structure patterned using the multiple exposure method. The diameter of the patterned holes was measured to be 552 nm with a lattice constant of 1.15 µm. The simulated response shows a reflection peak at 1559 nm with a 3nm linewidth. The performance of the guided mode resonance filter was determined experimentally using a 350 µm collimated beam from a tunable laser with an operating wavelength range of 1520 nm to 1630nm. The measured resonant peak was centered at 1557 nm with a 5.6 nm linewidth. The deviation from predicted linewidth is due to local variation in the fill fraction resulting from multiple exposure technique and a slight deviation in etch depth due the under exposure of the grating which was designed to provide a patterned feature size 800 nm as per the mask design.

The fabricated space variant transmission and reflection filters were characterized by inspection under a scanning electron microscope (SEM). The center of a lens in the array was located under the SEM. The radius of the patterned feature was measured at multiple radial locations from the center of a single lens. SEM images of the fabricated filters with variable fill fraction are show in Figure 6.10(a). The diameter of the holes at the center of the pattern was
662 nm, and increased radially to 733 nm. On a 1.15 µm period hexagonal grid, this corresponds to a fill fraction variation from 0.43 at the center to 0.37 at the edge of the unit patterned cell. The fill fraction variation followed a curve that was a result of two effects. The variation in feature size as a function of dose had a non-linear dependence upon dose in the operating regime. The spatial intensity variation across the pattern was quadratic. The resulting fill fraction variation was approximately linear. This fill fraction variation was repeated on a square grid of 300 µm corresponding to the period of the lens array that was used for the overlay exposure.

Figure 6.9: (a) SEM image of the fabricated grating on the guided mode filter element. (b) Corresponding measured spectral reflection from the device.

Spectral reflection was measured on the filters with variable fill fractions. The peak of the resonance was at 1552.4 nm corresponding to the diameter holes at the center of the patterns. The side lobe suppression was 10 dB and the linewidth was 9 nm which was wider than that obtained for the filter with no duty cycle variation. This can be explained by considering that multiple fill fractions that have slightly shifted spectral resonances were illuminated by the beam. The spectral reflection peak corresponded to maximum reflection from the features at the center of the space variant GMR mirror since the maximum intensity in the input Gaussian beam was at the center of the beam.
Figure 6.10: (a) Fill Fraction variation as a function of spatial location.  (b) Spectral measurement on the filters with fill fraction variation

The reflected beam profiles were simulated as a function of wavelength and are shown in Figure 6.11(a). Below resonance, the spatial reflection follows a Gaussian profile. As the wavelength approaches resonance, the intensity of the peak increases and reaches a maximum at the resonant wavelength. Above resonance the reflection profile has a central null that is 13% below peaks on either side. The corresponding simulated transmission profiles as a function of wavelength for a Gaussian input are shown in Figure 6.11(b). The transmission profiles vary rapidly on either side of the resonant peak wavelength. Below resonance a flat top profile is obtained with a small 2% dip at the center. This wavelength was chosen to maximize the flat top profile aspect ratio. At resonance, a transmission dip of 13% is obtained with two humps on either side of this dip. Above resonance, an apodized Gaussian transmission profile is achieved. The FWHM of the apodized Gaussian increases further away from resonance and matches input Gaussian width far from resonance.
Figure 6.11: (a) Simulated spatial reflectivity as a function of wavelength and (b) corresponding transmission profiles for a Gaussian input beam

The transmission profiles were characterized experimentally by illuminating the filter element with wavelength dependent space variant reflection using the tunable laser output and imaging the transmission onto a CCD camera and the results are summarized in Figure 6.12. The transmission profiles were measured below, at and above resonance. The transmitted power was measured using a power meter at the wavelengths of interest and the transmission ratio was factored when comparing to the simulated profiles. A flat top profile with a 1.3% dip in transmission at the center was obtained below resonance. The measured power transmission from the input beam of 300 µW was found to be 156 µW. At resonance, the central null had a transmission dip of 11% compared to the 13% predicted. This deviation is due to the wider resonance that was measured spectrally resulting in reduced suppression of the illumination wavelength by the adjacent spatial regions. The measured transmission was 120 µW (40%) corresponding to the increased transmission within the central dip. The apodized Gaussian was measured to have a FWHM of 130 µm compared to the predicted values of 120 µm. The transmitted power was measured to be 150 µW (50%). The experimental measurements agree well with the predicted values.
Figure 6.12: Experimentally measured transmission profiles. (a) Input Gaussian beam, (b) Flat top profile below resonance (c) Central null in transmission at resonance and (d) Reduced diameter Gaussian beam is obtained above the measured spectral resonance.

The reflection images were obtained by placing a beam splitter in the beam path before the space variant GMR mirror. The propagation distance to the mirror was ~ 1cm and the beam was 400µm wide when incident upon the filter. The period of the lens array was 300 µm as mentioned earlier. The reflection profile encountered by the broadened beam was calculated by considering that the same spatial reflection was repeated on each lens in the array. The simulated reflection profile is shown in Figure 6.13 (a). The spatial extent of one lens in the array is indicated by the vertical black lines. The reflection curves undergo a sharp transition at this point. As the wavelength of illumination was scanned from below resonance to resonance,
Figure 6.13: (a) The Gaussian beam after propagation illuminates more than one lens in the array. (b) As a result, the reflection profile encountered by the beam at the GMR was modified.

The device was illuminated at the measured resonant wavelength of 1552.4nm. A part of the reflected light was re-directed to an imaging port by the beam splitter and imaged on to a CCD camera. The reflected light propagated 6.2cm from the space variant mirror surface to reach the
detector plane of the CCD camera. The beam diffraction due to propagation was simulated numerically using a Rayliegh-Sommerfield diffraction integral. The beam profile was significantly modified after propagation as shown in Figure 6.14 compared to the reflection profiles obtained at resonance close to the device.

![Figure 6.14: (a) Simulated profile of the reflected beam close to the space variant GMR mirror at resonant illumination (b) Simulated beam profile at the detector plane after propagation of 6.2 cm at resonant illumination.](image)

The reflected beam profile from the space variant mirror was measured at the resonant wavelength. Following this, the diffraction of the 320µm beam due to propagation was measured by replacing the space variant GMR mirror with a broadband planar dielectric mirror at the same location. The results are summarized in Figure 6.15. The reflected beam from the

![Figure 6.15: Measured beam profiles when the illumination wavelength was (a) at resonance and (b) above resonance.](image)
space variant mirror agrees well with the simulated beam profiles after propagation. The reflected beam from the GMR mirror has a wider spread compared to the Gaussian beam reflected from the dielectric mirror as expected.

6.5 Summary

Guided-mode resonance filter elements with space-variant reflection profiles were designed and demonstrated. The variable reflection profiles were generated by modulating the duty cycle of the 2D grating layer of the GMR with a novel multiexposure technique, thus providing a continuous gradient across the structure. While this results in a broader reflection spectral peak, predictable wavelength-dependent reflection profiles were achieved. The experimentally measured values correspond closely with the model simulations. These elements represent novel space variant spectral mirrors that can be applied to spatial beam shaping and transverse mode control in high energy laser cavities since they are constructed purely with low loss dielectric materials. Moreover, the added spectral variations combined with the spatial control may provide for other novel applications in computational imaging and sensing. Additional features for polarization filtering can also be incorporated into the structure to make a more robust filtering technique for more complex cavities or imaging systems.
7 CONCLUSIONS

The research presented in this dissertation has explored novel micro optical components with multiplexed spatial and spectral functionality. Different solutions were explored and implemented to engineer and condition the near and far-field response of the incident infra-red beam using composite structures. The versatility of the solutions presented here makes them useful in a variety of application areas. The space variant micro optical elements were designed to provide frequency dependent transmission and reflection responses that can be utilized in applications such as graded reflectivity laser mirrors, spatial and spectral pupil filtering advanced imaging, and engineered illumination systems. In this dissertation, a technique for the modulating the fill fraction of one-dimensional and two dimensional grating structures was demonstrated using projection lithography for the first time. Decoupling the grating exposure step from the step that induces the spatial variation in fill fraction makes it a powerful method that is applicable in a variety of platforms. Designed grating variations were generated accurately and reliably.

The optical response of guided mode resonance filter elements and diffraction gratings operated in Littrow condition was tailored to provide frequency dependent spatial and spectral beam shaping. For the first time, frequency dependent spatial beam shaping in transmission and reflection was demonstrated using guided mode resonance effects. The experimentally measured spatial beam profiles closely matched the model predictions. The spectral linewidth from the space variant guided mode resonance filter was wider than a filter with no fill fraction modulation as a result of the combined resonances arising from the different fill fractions that were illuminated by the beam.
Space variant diffraction gratings operated in Littrow condition were used as the external feedback element to provide graded reflection profiles resulting significant enhancement of the far-field beam profiles and spatial brightness in broad area laser diodes. The far field enhancement was achieved at high pumping conditions making the lasers suitable for applications such as second harmonic light generation, laser machining and ablation.

Space variant optical transmission filters that provide wavelength tunable spatial transmission filtering were demonstrated by incorporating 8-level charge 2 diffractive vortex elements and analog lens arrays. The devices with the vortex elements integrated in the defect layer provide triangular wedge shaped zones of spatial transmission that have a wavelength dependent orientation. The devices with the analog lens array transmit annular rings of wavelength dependent diameter. Overall, excellent agreement was obtained between the experimental spectral and spatial measurements and the model predictions for all the devices. These devices are enabling and can lead to novel system level functionalities and miniaturization.
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