Micro-optic-spectral-spatial-elements (mosse)

2007

Alok Ajay Mehta

University of Central Florida

Find similar works at: http://stars.library.ucf.edu/etd

University of Central Florida Libraries http://library.ucf.edu

Part of the Electromagnetics and Photonics Commons, and the Optics Commons

STARS Citation

http://stars.library.ucf.edu/etd/3262

This Doctoral Dissertation (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
MICRO - OPTIC - SPECTRAL - SPATIAL - ELEMENTS: MOSSE

by

ALOK AJAY MEHTA
B.S. OPTICAL ENGINEERING University of Arizona, 2001
M.S. OPTICS University of Central Florida, 2003

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the College of Optics / CREOL&FPCE
at the University of Central Florida
Orlando, Florida

Fall Term
2007
Major Professor: Eric Johnson
ABSTRACT

Over a wide range of applications, optical systems have utilized conventional optics in order to provide the ability to engineer the properties of incident infra-red fields in terms of the transmitted field spectral, spatial, amplitude, phase, and polarization characteristics. These micro/nano-optical elements that provide specific optical functionality can be categorized into subcategories of refractive, diffractive, multi-layer thin film dichroics, 3-D photonic crystals, and polarization gratings. The feasibility of fabrication, functionality, and level of integration which these elements can be used in an optical system differentiate which elements are more compatible with certain systems than others. With enabling technologies emerging allowing for a wider range of options when it comes to lithographic nano/micro-patterning, dielectric growth, and transfer etching capabilities, optical elements that combine functionalities of conventional optical elements can be realized. Within this one class of optical elements, it is possible to design and fabricate components capable of tailoring the spectral, spatial, amplitude, phase, and polarization characteristics of desired fields at different locations within an optical system. Optical transmission filters, polarization converting elements, and spectrally selective reflecting components have been investigated over the course of this dissertation and have been coined “MOSSE,” which is an acronym for micro-optic-spectral-spatial-elements. Each component is developed and fabricated on a wafer scale where the thin film deposition, lithographic exposure, and transfer etching stages are decoupled from each other and performed in a sequential format. This facilitates the ability to spatially vary the optical characteristics of the different MOSSE structures across the surface of the wafer itself.
To my family, friends, and coworkers who have provided me with support and inspiration throughout the course of this graduate school journey.
ACKNOWLEDGMENTS

The completion of the work presented in this dissertation would not have been possible without the assistance and guidance of many individuals that I have been grateful to have had the opportunity to work with. I was provided with a unique opportunity to work within a state of the art clean room facility built up under the leadership and guidance of Dr. Eric G. Johnson within the College of Optics and Photonics at the University of Central Florida in Orlando, Florida. I am grateful for all of his tutelage, advice, and support over the years that have served as the foundation for my development over the years into a proficient researcher and engineer. I would like to thank Dr. Oleg Smolski and all of my former and present Micro-Photonics Group members, who allowed me to explore and investigate a broad range of optical technologies which I subsequently utilized as the backbone of my dissertation work. I would like to also thank all my family members for their never ending support during this graduate school experience that got me through a lot of tough situations.
# TABLE OF CONTENTS

LIST OF FIGURES ................................................................................................................................. ix
LIST OF TABLES ........................................................................................................................................ xiv

1. CHAPTER I: INTRODUCTION and BACKGROUND ........................................................................ 1

1.1 OPTICAL TRANSMISSION FILTERS ...................................................................................... 1

1.1.1 BROADBAND OPTICAL TRANSMISSION FILTERS .......................................................... 2

1.1.2 NARROWBAND OPTICAL TRANSMISSION FILTERS ..................................................... 6

1.2 OPTICAL REFLECTION FILTERS ............................................................................................. 10

1.2.1 BROADBAND OPTICAL REFLECTION FILTERS ............................................................. 10

1.2.2 NARROWBAND OPTICAL REFLECTION FILTERS ......................................................... 11

1.3 POLARIZATION CONVERTING ELEMENTS (PCE’S) ............................................................. 16

1.3.1 FORM-BIREFRINGENT SUB-WAVELENGTH STRUCTURES ........................................ 17

1.3.2 AUTO-CLONING OF LOW ASPECT RATIO STRUCTURES ........................................... 20

1.4 MICRO OPTIC SPECTRAL SPATIAL ELEMENTS: MOSSE ................................................... 22

1.4.1 SPACE VARIANT, NARROW-BAND, OPTICAL TRANSMISSION FILTER ..... 23

1.4.2 SPACE TYPE-MOSSE: SPATIALLY POLARIZING AUTO CLONED ELEMENTS ..................... 24

1.4.3 FIBER RESONATOR SPECTRALLY SELECTIVE FEEDBACK ELEMENTS ..................... 27

2. CHAPTER II: SPACE VARIANT OPTICAL TRANSMISSION FILTERS ..................................... 30

2.1 COMPONENT DESCRIPTION ................................................................................................. 31

2.1.1 MULTILAYER DIELECTRIC STACK CONTRIBUTION TO FILTER PERFORMANCE .................. 33

2.1.2 NANO-PATTERNING/ETCHING OF HOLE-ARRAY CONTRIBUTION TO FILTER PERFORMANCE ............................................................................................................... 35

2.2 FABRICATION PROCESS FLOW ......................................................................................... 40

2.2.1 PROCESS FLOW OVERVIEW ......................................................................................... 41

2.2.2 THIN FILM CHARACTERIZATION ................................................................................... 42

2.2.3 PATTERNING OF HOLE-ARRAY UTILIZING PROXIMITY EFFECT ................................... 44

2.3 EXPERIMENTAL TEST DATA ............................................................................................... 45

2.3.1 SPATIAL, SPECTRAL TRANSMISSION CHARACTERIZATION ..................................... 45
LIST OF FIGURES

Figure 1-1  (a) Rendition of dielectric based Fabry-Perot type optical transmission filter with
(\(\lambda/4\)) dielectric mirrors forming reflectors for resonator. (b) Spectral transmission
characteristics of filter as central layer thickness is varied..................................................... 4
Figure 1-2: High transmission efficiency, narrow line-width optical transmission filter based on
guided mode resonance effects as demonstrated in [7]........................................................... 8
Figure 1-3: Wide field of view narrow line-width spectral filter based on introduction of periodic
defects into a 2-D photonic crystal structure as demonstrated in [9]...................................... 9
Figure 1-4: (a) Conventional alternating (\(\lambda/4\)) thickness SiO/SiN dielectric layers forming
broadband reflector. (b) RCWA simulation of reflectance band and characteristic side bands
............................................................................................................................................... 11
Figure 1-5: 20 pairs of alternating SiN/SiO layers of (3\(\lambda/4n\)) thicknesses demonstrating decrease
in reflectance peak bandwidth. .................................................................................................. 12
Figure 1-6: 20 and 40 pairs of alternating SiN/SiO layers of (3\(\lambda/4n\)) thicknesses demonstrating
decreased reflectance peak bandwidth.................................................................................. 13
Figure 1-7: Geometrical depiction of double layer waveguide grating GMRF............................ 15
Figure 1-8: (a) GMRF structure definition using square lattice arrangement and (b) RCWA
simulation demonstrating high reflectance efficiency at the wavelength of interest and
narrow line-width.................................................................................................................. 16
Figure 1-9: Phase function for linear to azimuthal/radial polarization conversion. ..................... 20
Figure 1-10: Auto-cloned polarization splitter as demonstrated in [9]........................................ 21
Figure 1-11: Spatially variant optical transmission filter ............................................................. 24
Figure 1-12: Rendition of SPACE-MOSSE: Spatially polarizing auto-cloned elements........... 26
Figure 1-13: DCOFL operated in external cavity configuration with GMRF providing spectral feedback. ............................................................. 29

Figure 2-1: Spatially variant optical transmission filter MOSSE structure. ........................................... 32

Figure 2-2: RCWA modeling results overlaid on experimentally determined transmission characteristics of dielectric component of MOSSE structure ........................................ 35

Figure 2-3: Spatially variant optical transmission filter MOSSE structure and SEM image of hole-array patterning/ transfer etch over 2 cmx2cm area into multilayer dielectric stack.... 36

Figure 2-4: RCWA results demonstrating ability to position transmission peak within stop band through variation of hole diameter size of individual arrays. ........................................ 38

Figure 2-5: 1st order model, 2nd order curve fit, and RCWA predictions of peak transmission location as function of lattice constant of hole array with constant hole diameter of 370nm. ........................................................................................................ 40

Figure 2-6: Fabrication process flow for MOSSE Tx filter .......................................................... 41

Figure 2-7: Optical characterization of refractive index of SiO/SiN films ........................................... 43

Figure 2-8: SEM images of nano-structured hole-arrays as dose increases from 1500 to 1700 µ C/cm2 .......................................................................................................................... 45

Figure 2-9: (a) Fabricated and diced Tx filter: 2 cm x 2cm sample (b) and (c): SEM images of two different zones on 4” sample patterned with 367 and 440 nm hole diameters .......... 45

Figure 2-10: Experimental data for filters with two different hole diameter arrays patterned on single 4” wafer .......................................................... 46

Figure 2-11: SEM images of 3 zones on 4” wafer sample patterned and etched with different lattice constants ........................................................................ 47
Figure 2-12: Experimental transmission as function of wavelength overlaid with predicted transmission response incorporating a 0.15° of tapering into RCWA model....................... 49
Figure 2-13: RCWA results for transmission peak line-width spectrum as function of # DBR pairs....................................................................................................................................... 51
Figure 2-14: $R_{\text{eff}}$ of DBR stacks as function of # pairs of layers that make up mirror. ............... 52
Figure 2-15: Transmission peak line-width as function of # DBR pairs RCWA (red) and 1st order model (blue) .......................................................................................................................... 53
Figure 2-16: Transmission spectrum as function of plane wave angle of incidence .................... 54
Figure 3-1: SPACE type MOSSE structure rendition................................................................... 58
Figure 3-2: Pattern used in e-beam lithography for binary template fabrication......................... 61
Figure 3-3: Birefringence of SPACE device in terms of film thicknesses and longitudinal duty cycle. ..................................................................................................................................... 63
Figure 3-4: Fabrication process flow for PCE binary SiO$_2$ substrate template. ......................... 64
Figure 3-5: SEM images of etched SiO$_2$ binary patterns using optimized e-beam dose ........... 66
Figure 3-6: SEM images of top surface of binary SiO$_2$ template (a) top view of vortex center (b) cross-section of etched template with chrome mask remaining. ............................................. 68
Figure 3-7: SEM images of top surface of SPACE-based PCE device demonstrating triangular topography resulting from multilayer auto-cloning deposition process onto binary template substrate. .......................................................................................................................... 71
Figure 3-8: Experimental setup for optical characterization of SPACE device ......................... 72
Figure 3-9: SPACE component output beam demonstrating purely (a) radial and (b) azimuthal polarization distribution.................................................................................................................. 73
Figure 4-1: (a) Geometrical depiction of dual layer waveguide grating GMRF (cross-section) (b) hole array patterns for grating layer (surface view) ............................................................... 78

Figure 4-2: (a) and (b): RCWA simulation of spectral feedback properties hexagonal lattice symmetry GMRF design within c-band and over pump band (c) and (d): RCWA simulation of spectral feedback properties square lattice symmetry GMRF design within c-band and over pump band..................................................................................................................... 81

Figure 4-3: Reflected spectrum from DW-GMRF structure with gain bandwidth of doped- DCOF superimposed onto figure...................................................................................................... 83

Figure 4-4: AFM image of thinned S1805 resist layer patterned using GCA Stepper ............... 86

Figure 4-5: AFM data of chrome masking layer with photoresist layer remaining................... 87

Figure 4-6: AFM data of etched GMRF with chrome masking layer remaining ...................... 88

Figure 4-7: SEM image of top surface of HGMRF................................................................. 89

Figure 4-8: Experimental reflection data of HGMRF................................................................ 90

Figure 4-9: SEM images of hole-arrays patterned in ZEP-520A. ............................................. 91

Figure 4-10: (a) SEM image of SGMRF patterned in ZEP-520A. (b) Dark field microscope image of patterned SGMRF .................................................................................................. 93

Figure 4-11: AFM data of hole-array pattern transfer etched into chrome masking layer ......... 94

Figure 4-12: AFM data of final SGMRF component ................................................................ 95

Figure 4-13: Experimental data for reflection characterization of SGMRF design filter .......... 96

Figure 4-14: Experimental test setup using HGMRF as external feedback element in DCOFL. 97

Figure 4-15: LIV characteristics of MM pump module source .............................................. 99

Figure 4-16: Spectral content of pump beam at drive current of 2A ........................................ 99

Figure 4-17: ASE Spectrum from DCOFL ............................................................................. 100
Figure 4-18: Spectral content of external cavity DCOFL output ............................................... 101
Figure 4-19: LI characterization and SM output image of external cavity DCOFL output ...... 102
Figure 4-20: Input MM Pump Power vs. Output Wavelength Stabilized Power ....................... 103
Figure 5-1: (a) Photograph of Quintel mask aligner exposure system (b) schematic of contact lithography process ............................................................................................................. 106
Figure 5-2: (a) Microscope image of 750 nm diameter hole-array printed in photoresist (b) SEM image of input to MMI device with 980 nm line-width (c) Littrow grating with 800 nm line width printed in photoresist ............................................................................................................. 108
Figure 5-3: (a) G-line GCA stepper (b) basic schematic of exposure optical system w/in stepper (c) Detailed schematic of stepper exposure column w/ Koehler illumination scheme...... 110
Figure 5-4: AFM images of two different zones contained within individual die with non-optimized values for dose and focus offset................................................................. 112
Figure 5-5: AFM data of two different zones contained within individual die with focus offset parameter and dose trade-off partially optimized................................................................. 113
Figure 5-6: AFM of die where dose and focus offset parameters have been optimized ......... 114
Figure 5-7: (a) Leica 5000+ EBPG system used in this work (b) schematic of electron beam column (Leica Vector Beam Writer) ................................................................................................. 115
Figure 5-8: Target grid for e-beam lithographic exposures of hole-arrays......................... 116
Figure 5-9: Hole diameter increase as dose is increased. ......................................................... 117
Figure 5-10: STS Multiplex PECVD electronics rack and chamber schematic (courtesy of STS) ............................................................................................................................................... 119
Figure 5-11: Wavelength dependent index of refraction of SiO (blue) and SiN (red) dielectric layers. ............................................................................................................................................... 122
LIST OF TABLES

Table 1-1: Range of refractive index achievable using PECVD technique .............................................. 3
Table 1-2: Comparison between high/low refractive index materials ...................................................... 18
Table 2-1: Process parameter summary for PECVD of dielectric stack .................................................. 34
Table 2-2: Dry etching parameter summary ............................................................................................... 42
Table 3-1: Summary of grating parameters within overall patterned and etched template area . 65
Table 3-2: Summary of etching process parameters ................................................................................. 67
Table 3-3: Summary of PECVD process parameters ................................................................................. 69
Table 4-1: Summary of grating parameters for 2 different GMRF designs ............................................... 79
Table 4-2: DW-GMRF Design Parameters ................................................................................................. 82
Table 4-3: Summary of PECVD process parameters ................................................................................. 84
Table 4-4: Summary of etching process parameters .................................................................................. 88
Table 5-1: Generic photolithographic flowchart for pattern transfer into substrate material using positive photoresist .............................................................................................................. 105
Table 5-2: Process parameter summary for PECVD SiO/SiN dielectric layers ........................................ 120
Table 5-3: Sellmeier coefficient for curve fitting and extrapolation out to longer wavelengths. 121
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Auto-Cloned</td>
</tr>
<tr>
<td>AFM</td>
<td>Atomic Force Microscope</td>
</tr>
<tr>
<td>AR</td>
<td>Anti-Reflection</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>CP</td>
<td>Circular Polarization</td>
</tr>
<tr>
<td>DCOF</td>
<td>Double Cladding Optical Fiber</td>
</tr>
<tr>
<td>DOE</td>
<td>Diffractive Optical Element</td>
</tr>
<tr>
<td>EBPGS</td>
<td>Electron Beam Pattern Generating System</td>
</tr>
<tr>
<td>FP</td>
<td>Fabry-Perot</td>
</tr>
<tr>
<td>GMR</td>
<td>Guided-Mode Resonance</td>
</tr>
<tr>
<td>GMRF</td>
<td>Guided-Mode Resonance Filter</td>
</tr>
<tr>
<td>HGMRF</td>
<td>Hexagonal Guided Mode Resonance Filter</td>
</tr>
<tr>
<td>NOE</td>
<td>Nano-Optical Element</td>
</tr>
<tr>
<td>PC</td>
<td>Photonic Crystal</td>
</tr>
<tr>
<td>RCWA</td>
<td>Rigorous Coupled-Wave Analysis</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>SGMRF</td>
<td>Square Guided Mode Resonance Filter</td>
</tr>
<tr>
<td>SiN</td>
<td>Silicon Nitride</td>
</tr>
<tr>
<td>SiO</td>
<td>Silicon Oxide</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse Electric</td>
</tr>
<tr>
<td>Tx</td>
<td>Transmitted Component</td>
</tr>
</tbody>
</table>
1. CHAPTER I: INTRODUCTION and BACKGROUND

Conventional optics have been incorporated into optical systems in order to provide the ability to engineer the properties of incident infra-red fields in terms of the transmitted field spectral, spatial, amplitude, phase, and polarization characteristics. These micro/nano-optical elements that provide specific optical functionality can be categorized into subcategories of refractive, diffractive, multi-layer thin film dichroics, 3-D photonic crystals, and polarization gratings. The feasibility of fabrication, functionality, and level of integration which these elements can be used in an optical system differentiate which elements are more compatible with certain systems than others. With enabling technologies emerging allowing for a wider range of options when it comes to lithographic nano/micro-patterning, dielectric growth, and transfer etching capabilities, optical elements that combine functionalities of conventional optical elements can be realized. Within this one class of optical elements, it is possible to design and fabricate components capable of tailoring the spectral, spatial, amplitude, phase, and polarization characteristics of desired fields at different locations within an optical system. Because of this ability to engineer the properties of all aspects of an input field within one class of optical elements, these optical elements will be referred to as MOSSE, or micro-optic-spectral-spatial-elements.

1.1 Optical Transmission Filters

An overview of existing optical transmission filter technologies will be presented in order to explain the motivation for the MOSSE presented which provides spatial variation of the transmission spectral response of the optical filter over a finite aperture. This is presented in the framework of different dielectric based optical filters that require additional processing during
intermediate growth steps in order to realize spatially variant optical transmission filters. These dielectric optical transmission filters can be grouped and will be discussed in two categories, broadband \((\Delta \lambda_{Tx,\text{peak}} > 5\text{nm})\) and narrowband \((\Delta \lambda_{Tx,\text{peak}} < 5\text{nm})\) filters.

1.1.1 Broadband Optical Transmission Filters

The thin film deposition necessary to realize a high transmission efficiency, dielectric based, broadband, optical transmission filters can be performed using different film deposition techniques such as spin on deposition, physical vapor deposition (PVD), low pressure chemical vapor deposition (LPCVD), or plasma enhanced chemical vapor deposition (PECVD). Spin on deposition of dielectric materials provides good planarization and gap filling properties, but is limited in the deposition of multi-layer dielectric structures. For the deposition of the dielectric thin films used to create the MOSSE structures presented here, PECVD of the thin film layers provides the mechanical stability, uniformity across a 4” wafer substrate, and index of refraction that is required. In plasma based deposition systems, the optical/mechanical properties of the thin films are contingent on the ratio of the precursor gases and on plasma-surface interactions during film growth. Under the appropriate precursor gases, pressure, and temperature conditions, the following table summarizes the range of possibilities in terms of index of refraction that can be deposited on substrates utilizing the PECVD technique. There is sufficient amount of options for deposited materials to cover the range required for interference filter fabrication and, unlike PVD processes traditionally used to fabricate optical filters, the entire range of options for refractive index is complete over this range without any gaps.
Early renditions of dielectric based optical transmission filters included the Fabry-Perot type interference filter which consisted of a dielectric spacer layer in between two silver partially reflecting films. In [1], combinations of silver layers with dielectric layers were applied in order to reduce the absorption of the silver layers. This approach was inherently limited in maximum transmission efficiency due to the absorption of the silver layers. With the advent of the previously mentioned thin film deposition techniques, an all dielectric multilayer rendition of the Fabry-Perot filter can be fabricated consisting of a dielectric spacer layer in between quarter wave stack dielectric mirrors to form the resonant cavity. Figure 1-1 depicts a rendition of a Fabry-Perot, dielectric based optical transmission filter along with rigorous coupled wave analysis (RCWA) predicted spectral transmission response of the structure using two different spacer layer thicknesses. From this figure, as the thickness of the spacer layer is increased, the transmission peak within the stop band shifts towards longer wavelengths. The filter has a

Table 1-1: Range of refractive index achievable using PECVD technique

<table>
<thead>
<tr>
<th>Material Description</th>
<th>LOW INDEX</th>
<th>MEDIUM INDEX</th>
<th>HIGH INDEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO₂</td>
<td>![Graph]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ta₂O₅</td>
<td>![Graph]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO₂: C:H</td>
<td>![Graph]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiN₁.₃:H</td>
<td>![Graph]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂Nₓ:H</td>
<td>![Graph]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPOS</td>
<td>![Graph]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPHC</td>
<td>![Graph]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂:H</td>
<td>![Graph]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂:F</td>
<td>![Graph]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPFC</td>
<td>![Graph]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Refractive Index at 550 nm

1.2 1.4 1.6 1.8 2 2.2 2.4 2.6
transmission efficiency of the transmission peaks within the stop band of approximately 78%, with a FWHM of ~ 2 nm.

Figure 1-1 (a) Rendition of dielectric based Fabry-Perot type optical transmission filter with (\(\lambda/4\)) dielectric mirrors forming reflectors for resonator. (b) Spectral transmission characteristics of filter as central layer thickness is varied.

In order to provide a spatially varying functionality to a filter of this type, intermediate fabrication steps must be added to the overall process flow to spatially alter the thickness of the central spacer layer before the top dielectric stack is deposited. This entails lithography and etching fabrication steps following the dielectric growth of the central spacer layer. 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:

$$F = \frac{4(R_1R_2)^{1/2}}{[1-(R_1R_2)^{1/2}]^2} \quad 1.1$$

$$T_{\text{MAX}} = \frac{T_1T_2}{[1-(R_1R_2)^{1/2}]^2} \quad 1.2$$

$$\Phi = \frac{2\pi n_f d_f \cos(\theta)}{\lambda} + \frac{\delta_1 + \delta_2}{2} \quad 1.3$$

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

$$T = \frac{T_{\text{MAX}}}{1 + F \sin^2(\Phi)} \quad 1.4$$

From equation 1.3, it can be seen that the maximum transmission occurs when $\Phi = p\pi$ where $p = 0, \pm 1, \pm 2$. Because the dielectric mirrors are comprised of quarter wave thickness layers, the phase change upon reflection from the stacks, $\delta_{1,2}$, is accurately zero. Thus, for normally incident light, the peak transmission peak within the stop band can be described as in terms of the spacer index, $n_{\text{HI}}$, and the thickness of the spacer layer, $d$.

$$\lambda_{\text{peak}} = \frac{2n_{\text{HI}} d}{p} \quad 1.5$$

In the case of this particular filter, it is necessary to maintain a single resonance within the stop band, thus the value of $p$ is set to one. From equation 1.5, 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 line-widths 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 both sides of the spacer layer and altering the index contrast of the materials used. This can enhance the FWHM of the transmission peak line-width from ~ 4 nm to ~ 0.1 nm. Depending on the wavelength of operation and subsequent material constraints, a large number of deposited layers may not be the most feasible approach to the filter fabrication wise. Other forms of dielectric based optical transmission filters that utilize other spectral filtration mechanisms that are inherently narrowband with respect to the transmission peak within the stop band have also been demonstrated and are introduced in the next section. Utilizing these mechanisms, it is possible to realize a space variant optical transmission filter; however, all the configurations entail a more involved fabrication process with additional processing required at intermittent steps in the dielectric film deposition process.

1.1.2 Narrowband Optical Transmission Filters

There are several different optical mechanisms that can be utilized to produce narrow line-width, high transmission efficiency optical filters that have been conceptually demonstrated in the past. The common ground for the design and fabrication of these different types of transmission filters
is the necessity to process intermittent layers during the overall thin film deposition process. In particular, [2] concluded that guided mode resonance (GMR) effects in multilayer waveguide grating structures can be utilized to produce narrow line-width and high peak response optical transmission filters. The GMR effect results in a sharp peak in the diffraction efficiency spectrum from the waveguide grating structures. At this resonance wavelength, for a particular range of wavelengths, angle of incidence, and grating parameters, there is a highly efficient exchange of energy between the reflected and transmitted waves. Through the integration of diffraction gratings into traditional thin film multilayer structures, this type of transmission filter produced a narrower line-width transmission response to a conventional Fabry-Perot filter with an equivalent number of dielectric layers. The principles governing the behavior of a filter of this type are derived from the diffractive, multi-layer dielectric, and waveguide characteristics of a dielectric based optical waveguide grating structure. The origin of this type of optical filter stems from research conducted on the spectral reflection filtering effects of waveguide grating structures and the GMR effect. [3]fabricated and experimentally verified the operation of a narrow line-width reflection filter, taking advantage of the zero order anomaly resonance properties of dielectric coated gratings. This concept was manipulated to create a transmission filter with approximately 90% transmission efficiency, but performance was limited due to a small side mode suppression ratio. This was achieved through the embedding of a transmission grating and experimentally verified in [4]. In [5] and [6], it was shown that filters incorporating thin film optics into these diffractive and waveguide structures, nearly ideal reflection filters with high transmission efficiency, narrow line-widths, and high side mode suppression ratios could be achieved. Merging the findings from the embedded transmission filter and realization of high efficiency reflection filters through incorporation of thin film optics, [7] demonstrated the results
of integrating resonant structures into multilayer thin film high reflectance structures to create transmission band pass filters. Through this combination of the dielectric mirror effect and asymmetrical GMR response of the waveguide grating structures, a 100 % transmission efficiency was demonstrated where the line-width of the filter response can be designed based on the modulation index and degree of mode confinement. Subsequent analysis by [8] demonstrated that by combining the effect of the high reflectance properties of a high/low refractive index quarter wave dielectric stacks with the resonance effect from the waveguide grating could achieve a narrower line-width than the embedded transmission filter design with fewer deposited layers, while maintaining a high transmission efficiency and high side mode suppression ratio. The basic filter structure is depicted in Figure 1-2.

Figure 1-2: High transmission efficiency, narrow line-width optical transmission filter based on guided mode resonance effects as demonstrated in [7]
The spectral transmission response of an optical transmission filters that operate under GMR conditions inherently has a strong dependence on the angle of incidence to the filter itself. If an application requires the optical filter to perform over a larger range of angle of incidence conditions, a different form of optical filters must be used. 2-D photonic crystal structures with periodic defects have been used to realize a wide field of view, narrow line-width spectral transmission filter as done in [9] and shown in the following figure.

Figure 1-3: Wide field of view narrow line-width spectral filter based on introduction of periodic defects into a 2-D photonic crystal structure as demonstrated in [9]
1.2 Optical Reflection Filters

Several different resonate applications require highly efficient dielectric based filters that function as spectrally selective optical reflection filters. Dielectric based optical reflection filters have been realized using many of the same techniques outlined in the proceeding section detailing optical transmission filters. The overview of the existing approaches to dielectric based optical reflection filters will be presented in two categories in terms of the bandwidth of the reflection spectrum provided from the filter, broadband ($\Delta\lambda_{Rx,peak} > 10$nm) and narrowband ($\Delta\lambda_{Rx,peak} < 1$nm).

1.2.1 Broadband Optical Reflection Filters

Conventional dielectric based broadband optical reflection filters have been traditionally fabricated utilizing quarter-wave thickness dielectric layers of alternating high-low refractive index material to produce the desired reflected band over a finite wavelength range. With the advent of PECVD technology allowing for the deposition of multiple dielectric layers with low mechanical (tensile and compressive) stress, uniformity over large areas, and the ability to grade the refractive index during the deposition process, these conventional filters have been enhanced further. The following figure depicts a conventional quarter wave multilayer stack of alternating high/low SiN/SiO layers deposited on a SiO$_2$ substrate. The RCWA simulations demonstrate the spectral reflectance characteristics of such a filter with 10 pairs of SiO/SiN layers around a wavelength of 1550 nm demonstrating the characteristic reflectance peak and surrounding side bands.
1.2.2 Narrowband Optical Reflection Filters

Narrow line-width, low side band suppression, highly efficient, reflection filters have numerous applications in WDM, hyper spectral imaging, resonator optics for laser cavities, and pulse shaping. Even though deposition processes and tooling have been optimized to minimize both tensile and compressive mechanical stress properties of the deposited films, material properties still ultimately limit the ability to feasibly fabricate narrow line-width, high efficiency reflection filters using a multiple thin film approach. In order to produce a narrow line-width reflectance filter, the two design considerations that need to be taken into consideration essentially can be decoupled between choosing materials that will provide the desired index contrast and, based off of the wavelength region of interest, determining the thicknesses of the layers to use. From the conventional broadband DBR filter depicted in Figure 1-5, by increasing the thicknesses of the
alternating SiO/SiN layers to $3\lambda/4n_{SiN/SiO}$ for the same number of pairs of layers, a narrowing of
the peak reflectance line-width is observed and depicted in the following figure.

![Graph](image)

**Figure 1-5: 20 pairs of alternating SiN/SiO layers of $(3\lambda/4n)$ thicknesses demonstrating decrease in reflectance peak bandwidth.**

It is important to note that the line-width of the reflectance peak has been noticeably decreased, however not to the extent where the filter would fit into the category of a narrow line-width filter staying with the criteria that $\Delta \lambda_{Rpeak} < 10$ nm. Increasing the layer thicknesses further provides no realistic advantage since even with this design, total dielectric stack thickness has been increased from 4.675 $\mu$m to 14.024 $\mu$m from the $(\lambda/4)$ and $(3\lambda/4)$ designs forcing the necessity for intermediate annealing steps that further complicate the fabrication process. The index contrast between the alternating layers determines the line-width of the reflected spectrum, while the total number of pairs layers determines the filter reflection efficiency. Staying with the $(3\lambda/4)$ design,
by changing the SiN material to a lower index SiO<N/sub> material, the line-width of the reflected spectrum can be further decreased, but at the expense of the efficiency for the same number of pairs of layers. The following figure displays the RCWA simulated results of the (3\(\lambda/4\)) filters using a SiO<N/sub> material with a refractive index of 1.6 demonstrating the ability to decrease the line-width of the reflected spectrum.

![Figure 1-6: 20 and 40 pairs of alternating SiN/SiO layers of (3\(\lambda/4n\)) thicknesses demonstrating decreased reflectance peak bandwidth.](image)
In order to reach a 70% maximum reflected efficiency, 40 pairs of (3λ/4) layers would be required with a total overall thickness of the stack being 28.048 μm. Additional lithographic and transfer etching steps are required at intermediate steps within the overall dielectric deposition process in order to provide the spatial variation of the reflectance spectrum across the device aperture. This, in addition to the additional annealing steps that would be required to be incorporated to the overall fabrication process flow to ensure uniformity across the filter aperture due to the large thickness of the multilayer dielectric stack, limits the overall feasibility of fabrication of these types of filters. Clearly, in order to realize a dielectric based, highly efficient, narrow line-width reflecting filter, an approach that involves a smaller number of deposited layers is desired that also possesses an overall fabrication process flow that would allow for the spatial variation of the spectral response across the filter aperture without the issues that arise with conventional multilayer thin film filters.

In [16] a new type of wavelength dependent reflecting filter was introduced that combined the wave-guiding properties of thin films with diffractive characteristics from sub-wavelength periodic structures that achieved the target performance figures of merit in terms of efficiency and narrow line-width. [17] demonstrated that filters of this type can be designed to provide high efficiency, narrow line-width, along with a high level of sideband suppression. The following figure depicts the basic geometry of a cross section of the filter being currently described.
Figure 1-7: Geometrical depiction of double layer waveguide grating GMRF.

Over a finite wavelength range, this filter was shown to possess sharp resonance behavior where all of the energy between reflected and transmitted waves was transferred, thus possessing the ability to function as a narrow line-width, highly efficient filter. Because this type of filter is a combination of a diffraction grating and thin film dielectric structure, there are two mechanisms that need to be taken into consideration in order to understand the behavior of these filters. Namely, these mechanisms are the principles of diffraction from a periodic structure and wave-guiding properties of a slab waveguide. The filter operates under specific resonance conditions that need to be satisfied in order for the incident plane wave to be phase matched to the leaky
waveguide modes supported by the structure. This leaky mode is strongly coupled to the zero-order propagating waves at resonance allowing for a highly efficient transfer of energy between the reflected and transmitted waves, thus these filters have been coined guided mode resonance filters (GMRF’s). It is useful to have filter responses that operate independent of polarization that have 90° rotational symmetry. The following GMRF depicted below has been evaluated using a RCWA formulism demonstrating the narrow line-width, high efficiency reflection characteristics of the filter.

![GMRF structure definition and RCWA simulation](image)

Figure 1-8: (a) GMRF structure definition using square lattice arrangement and (b) RCWA simulation demonstrating high reflectance efficiency at the wavelength of interest and narrow line-width.

1.3 Polarization Converting Elements (PCE’s)

Polarization converting elements (PCE) using sub-wavelength binary gratings to construct form birefringent devices have been used to generate radial and azimuthal polarized fields. These devices can be used to control the complex amplitude of the two incident, orthogonal polarizations depending on the degree of birefringence that is a function of the substrate optical
properties, orientation, and periodicity of the structure. For an incident linearly polarized field, the PCE components considered here will produce a radial or azimuthal output polarized field depending on the orientation of the device with respect to the incident field, or in other words, function as a half wave plate where one polarization component accumulates 180° more phase than the other polarization component after transmission through the device.

1.3.1 Form-birefringent Sub-wavelength Structures

The material properties of the substrate used to fabricate these types of polarization converting elements is the first design constraint needed to be taken into account. This is significant in terms of determining the feature sizes and aspect ratio of the sub-wavelength grating necessary to produce the desired amount of phase retardation. In the regime where the period of the grating is less than the wavelength of the incident field, provided there is a high enough index contrast, the grating effectively behaves as a homogeneous uni-axial material with a high level of birefringence. From effective index theory, the expression for the thickness of the grating in terms of the incident free space wavelength, \( \lambda_0 \), dielectric constants, \( \varepsilon_{//} \) and \( \varepsilon_{\perp} \), that the parallel and perpendicular polarization fields experience can be expressed as follows where the effective permittivities can be calculated as done in[10].

\[
d_x = \frac{\lambda_0}{2(\sqrt{\varepsilon_{//}} - \sqrt{\varepsilon_{\perp}})}
\]

For a standard, binary sub-wavelength grating, in order to achieve the \( \pi \)-phase retardation that results from etched binary structures at depth of \( d_\pi \), Table 1-2 summarizes a comparison between fabrication of the elements in a high index, GaAs material, as well as in a low index, SiO\(_2\) material.
Table 1-2: Comparison between high/low refractive index materials

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>GaAs</th>
<th>SiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive Index @ 1550 nm</td>
<td>3.3737</td>
<td>1.4511</td>
</tr>
<tr>
<td>Period</td>
<td>0.775 µm</td>
<td>0.775 µm</td>
</tr>
<tr>
<td>Filling Fraction</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>d₀</td>
<td>0.996 µm</td>
<td>5.76 µm</td>
</tr>
</tbody>
</table>

From this table it is evident that for the same grating design, the relatively high refractive index of GaAs allows for the ability to create high birefringence devices that have low aspect ratios. This is significant since the same structure in SiO₂ requires extremely high aspect ratio structures that are challenging to fabricate due to mask erosion and polymer re-deposition issues that complicate the transfer etch process. Essentially, as the refractive index is decreased, the aspect ratio of the resulting half wave structure increases. However, using a high refractive index material also results in a high reflectivity from the device, decreasing the transmission efficiency.

Polarization converting elements comprised of sub-wavelength gratings distributed in a discrete or continuous sub-wavelength grating layout across the substrate surface are considered in this work. Discrete grating layouts consist of equivalently sized zones of sub-wavelength gratings with uniform orientation, periodicity, and duty cycle that are rotated at discrete angles with respect to each zone. Effectively, the polarization of the transmitted field through the PCE can be controlled by changing the orientation of the sub-wavelength gratings relative to the incident field. In [11], a discrete space-variant sub-wavelength grating structure was utilized in a systems application to perform near-field polarimetry, where the orientation of the gratings were discretely laid out relative to the incident field. By adopting a discrete grating layout, all the individual gratings in each cell are of the same geometrical parameters, and the overall elements are unlimited in their dimensions. In [12], a discrete sub-wavelength distribution of the grating elements was implemented where the overall PCE consisted of 12 individual grating sections.
with \((\lambda/2)\) periodicities each rotated with respect to each other such that the grating vector was rotated by \(\pi/6\) relative to the previous cell. This GaAs based PCE provided linear to azimuthal polarization conversion, but had inherently significant reflection losses due to the material properties of the substrate.

Continuous grating layout based PCE devices were addressed in [13], where any desired output polarization state could be created by engineering the orientation of the form-birefringent element design spatially with respect to the incident linearly polarized field. For linear to azimuthal polarization conversion, the characteristic phase function describing the sub-wavelength grating layout has spatially varying periodicities which, for large aspect ratio devices, can lead to complications in the overall optimization of the fabrication process due to the feature size dependent lithography and transfer etching. As in the discrete grating layout scenario, a tradeoff between the index of refraction of the substrate material, the required aspect ratio for desired birefringence, and the reflective loss has to be taken into account. Upon selection of substrate materials, the phase function can be synthesized into a format compatible with the electron beam lithography pattern generator as depicted below in the figure depicting the structure to be written on the e-beam.
1.3.2 Auto-cloning of Low Aspect Ratio Structures

In both cases of discrete and continuous sub-wavelength grating layout approaches to PCE component design, the relationship between substrate index of refraction (and subsequent reflection losses) and amount of birefringence required limits the feasibility of device fabrication. To alleviate the material properties constraints, prior work by [14] demonstrated the ability to auto-clone multilayer films onto the surface of low aspect ratio binary template patterns. In doing so, the two main disadvantages to conventional fabrication of sub-wavelength based polarization splitting devices, namely reflective losses and fabrication related aspect ratio challenges from birefringence requirements, were overcome allowing for the realization of
dielectric based, high efficiency, polarization beam splitters. This was achieved through what was coined the “auto-cloning” process that occurs post deposition of multilayer thin films onto a binary template substrate. Essentially, through the deposition of multiple, alternating dielectric layers, an evolution of the template surface. For specific growth process conditions, this multilayer thin film deposition upon the surface of a binary template substrate results in an evolution in the template surface topography, morphing the cross-sectional surface geometry from square to triangular. Additional layers can be deposited while maintaining this triangular topography on the surface of the auto-cloned binary template. The following figure depicts the findings of [18] where an auto-cloned sub-wavelength binary grating was realized through the deposition of alternating a-Si/SiO₂ dielectric layers onto the binary template.

Figure 1-10: Auto-cloned polarization splitter as demonstrated in [9]
Thus, it is possible to utilize this process to compensate for the inherently low amount of birefringence provided from low index material based structures due to the ability to deposit virtually an unlimited number of dielectric layers onto the surface of the structure without altering the surface topography. This directly overcomes the fabrication related challenges that are inherent when using low index substrate materials to create sub-wavelength based polarization sensitive structures that require a high level of birefringence, and subsequently a large aspect ratio structure on the order of 1:100. Another important feature to note from this auto-cloning process, in relation to the findings in[10], where the triangular cross section, sub-wavelength grating structures for anti-reflective coatings demonstrated the highest anti-reflection efficiency. This will allow for the low reflectivity aspect of the desired PCE based in low index dielectric material to be realized.

1.4 Micro Optic Spectral Spatial Elements: MOSSE

In the sections prior, background information has been provided for dielectric based, pre-existing technologies currently and previously utilized to engineer the spatial, spectral, and polarization characteristics of infra-red fields. The different technologies were evaluated in terms of the overall optical functionality of the components, and of the complexity and feasibility of the overall fabrication processes. The MOSSE components introduced in this section demonstrate the ability to integrate the optical functionalities of spatial, spectral, and polarization beam control using composite structures. These composite structures are formed through the combination of micro and nano-scale lithographic/transfer etching techniques in conjunction with multilayer, dielectric, thin film, PECVD processes.
1.4.1 **Space Variant, Narrow-band, Optical Transmission Filter**

The first MOSSE component described here functionally, through a simplified fabrication process relative to current approaches, provides the ability to spatially vary the spectral transmission properties across the device aperture while maintaining a high transmission efficiency and relatively narrow transmission peak line-width. Conventional approaches to dielectric based optical transmission filters have been optimized with the advent of plasma enhanced chemical vapor deposition (PECVD) technologies. All of the three different approaches presented previously for the realization of narrow line-width optical transmission filters with the additional functionality of space variant wavelength dependent transmission involve masking, lithographic, and transfer etching fabrication processes at intermediate steps within the overall dielectric deposition process. The filter presented here utilizes a simplified fabrication approach inherent to the sequential process flow in which all additional masking, lithography, and transfer etching processing is performed post completion of the overall dielectric thin film deposition process. The planar geometry of this type of filter serves to facilitate for the monolithic integration of the filter into standard charge coupled device (CCD) based detector arrays to allow different pixels within the detector array to detect different wavelengths. This ability to tailor the spectral transmission characteristics across the filter aperture mapped to specific zones on a CCD array can be utilized in many different imaging applications. The following figure depicts a rendition of the filter presented here providing spatial variation of the wavelength dependent transmission characteristics across the filter aperture and the integration into a standard CCD array for infra-red imaging applications.
Two different spectral tuning mechanisms are investigated, specifically, two different approaches to the variation of the hole array parameters patterned and etched through the multilayer stack. In the first case, the lattice constants of each zone are fixed, while the hole diameter of the individual elements that comprise the hole-arrays is varied. In the second scenario, the hole diameter of the hole-arrays in each zone are fixed, while the lattice constant of each zone is varied.

1.4.2 **SPACE type - MOSSE: Spatially Polarizing Auto Cloned Elements**

As previously demonstrated in [12], a linear to azimuthal polarization converting element has been demonstrated that is comprised of a high aspect ratio form-birefringent grating patterned
and etched into a GaAs substrate. Based off of the material properties of the substrate (the high refractive index over the IR wavelength range), the necessary aspect ratio required for the desired amount of birefringence is realizable using standard lithographic and transfer etching technologies. However, as a direct consequence of the refractive index, the device suffered from significant reflection losses. This reflection loss issue could be addressed by moving to a lower refractive index substrate. However, the increased aspect ratio of the structure necessary to maintain the amount of birefringence required for half wave operation adds increasing complexity to the fabrication process as the aspect ratio can exceed 100:1 for standard oxide dielectric materials.

The GaAs based PCE technology can be further progressed utilizing the auto-cloning technique onto a low aspect ratio binary structure in SiO₂ material to create a form birefringent structure addressing both the reflection loss and aspect ratio issues associated with fabrication of PCE using low index dielectric materials as initially introduced in [20]. The SPACE structures presented here incorporates SiO/SiN thin films deposited onto a low refractive index SiO₂ substrate template to produce a low reflectance, high transmission efficiency, optimized birefringent structure. Through the use of low index materials in conjunction with the triangular surface topography originating directly as a result from the dielectric deposition auto-cloning process, PCE can be fabricated with a high level of birefringence without sacrificing overall component efficiency. The following figure depicts a rendition of the SPACE component presented utilizing the auto-cloning technique.
This SPACE component produces the effectively high aspect ratio (10:1) form birefringent gratings to convert a linearly polarized incident beam, at a wavelength of 1550 nm, to an azimuthally polarized output with more than 90 % efficiency. The SPACE structure birefringence was optimized in terms of the alternating SiN/SiO layer thicknesses used in the multilayer, auto-cloning deposition process.
1.4.3 Fiber Resonator Spectrally Selective Feedback Elements

Spectrally selective reflecting feedback elements such as Littrow gratings, volumetric Bragg grating, Fiber Bragg gratings (FBG’s), GMRF’s, and DBR stacks for example, have been integrated into semiconductor and fiber based laser resonator systems in order to provide wavelength stabilization to the resonator cavities in internal and external configurations. Specific to recent advances in double cladding doped optical fibers allowing for multimode pumping compatible with now available fiber pigtailed high power diode pump modules, double cladding optical fiber lasers (DCOFL’s) have conventionally been wavelength stabilized using a variety of spectral feedback mechanisms such as intracore FBG’s as demonstrated in [101]. This approach has been successfully implemented into single fiber laser systems, however, the scalability in terms of integration into array based systems remains limited from the serial fabrication process utilized in the creation of the FBG feedback elements. This was observed in [102] where overlap-written FBG’s were used in Er-doped fiber lasers, with each grating providing more than 96% reflectivity over an ~ 0.3 nm bandwidth with each grating written with a separate phase mask. Recently, [103], utilized interference based fabrication methods to realize a one dimensional GMRF directly on the end facet of the fiber gain media itself in order to provide the spectrally selective feedback into the resonator cavity. This approach was inherently limited in terms of the spectral feedback performance due to the fabrication limitations and polarization dependence of the 1-D GMRF.

The MOSSE component introduced in this section is used in a DCOFL operated in an external cavity configuration where the MOSSE component provides two optical functionalities. The component consists of a square lattice GMRF designed to satisfy two requirements, namely to provide a sharp reflectance resonance located within the gain bandwidth provided from the
DCOF and to transmit all the wavelengths contained within the emitting spectrum from our multimode diode pump module. Conventional fiber lasers operated in external cavity configurations require two critical alignments, fiber to collimation optics and collimation optics to feedback element. From the proof of concept demonstrated in this work, it is possible add another level of integration through the fabrication of a diffractive lens on the backside of this MOSSE component, thus requiring only one critical alignment between the DCOF and the MOSSE component. Moreover, this approach has potential for scalability in terms of the components being fabricated with standard semiconductor lithography tools in a wafer based fabrication process flow if arrays of these DCOFL’s are desired. The following figure depicts the DCOFL operated in an external cavity configuration where the pump light is injected through the backside of the GMRF into the DCOF. The GMRF side of the resonator provides a narrow line-width, high efficiency spectral feedback into the cavity, while the opposite, cleaved facet side of the DCOF provides a low reflection feedback. The selected lens, GMRF section can be combined into the MOSSE component introduced in this section via front to backside processing techniques. For initial conceptual verification, the GMRF and collimating optics will be inserted into the external cavity as individual elements.
An important feature that is a direct result of this particular external cavity pumping and feedback configuration is the size of the signal beam incident on the feedback GMRF. The advantages that arise from this system feature are discussed in chapter 4 in more depth as related to this particular system’s performance with respect to thermal and non-linear issues that become significant when scaling fiber laser systems to higher powers.
2 CHAPTER II: SPACE VARIANT OPTICAL TRANSMISSION FILTERS

The MOSSE presented here provides spatially variant optical transmission across the device aperture while maintaining a high transmission efficiency and narrow line-width in the transmission peak within a large transmission stop band. This MOSSE utilizes a simplified fabrication process, differentiating it from conventional space variant transmission filters which require additional processing at intermediate steps during the dielectric film deposition process.

As first introduced in section 1.1, standard dielectric Fabry-Perot type filters [1] and dielectric multilayer thin film high reflectance structures with embedded resonant structures [2] can be designed and optimized to provide narrow line-width, highly efficient transmission filters. With additional processing at intermediate stages within the overall dielectric deposition process, these types of filters can provide spatial variation of the spectral transmission characteristics across the filter aperture. In section 1.1.1, RCWA results depicted the ability to shift the wavelength location of the transmission peak in a conventional dielectric based FP transmission filter by altering the thickness of the central layer. This type of filter was comprised of high reflectance DBR stacks surrounding a central, cavity layer, forming the FP resonator. Through lithographic and transfer etch processing of across different zones on the surface of the central dielectric layer, it is possible to realize a standard FP transmission filter with space variant transmission functionality. Similarly, as demonstrated in [6], by altering the geometrical parameters of the central waveguide grating layer embedded between high reflectance high/low refractive index quarter wave dielectric stacks during the lithographic processing stage of the central layer, the transmission characteristics of the filter could be varied spatially across the filter surface. Both approaches are require lithographic and transfer etching processing at an intermediate stage within the overall dielectric deposition process. In doing so, it is necessary to address
planarization, uniformity, and alignment issues which require complex fabrication routines in order to maintain ideal filter cross-sectional geometries. The MOSSE transmission filter presented here provides the optical functionality of space variant transmission variation, while utilizing a more convenient and simplified fabrication process in comparison to conventional approaches. This is achieved by decoupling and sequentially performing the multilayer thin-film deposition, lithographic, and transfer etching stages of the overall process fabrication process flow.

This MOSSE transmission filter is investigated in terms of two different spectral tuning mechanisms that are introduced and evaluated in the sections that follow, supplemented by theoretical and experimental verification of transmission filter performance. In addition to the modeling performed for initial filter design purposes, the filter is further evaluated with respect to the spectral transmission line width as a function of the multilayer dielectric stack parameters and the impact of angle of incidence variation on filter performance.

2.1 Component Description

The mechanism by which the spectral and spatial tuning of a conventional Fabry-Perot transmission filter is provided via a fabrication process where all stages of the overall fabrication process flow are decoupled from each other and performed in a sequential fashion. The planar geometry of this type of transmission filters that are processed utilizing standard wafer based fabrication tooling allow them to be easily integrated into any planar detector plane. The following figure, Figure 1-1, depicts a rendition of the MOSSE, monolithically integrated onto the detector plane allowing for adjacent pixels within the charge coupled device (CCD) to detect different wavelengths [20].
The optical filter presented here can be described as a tunable 3-D Photonic Crystal (PC) or more generally, as a Fabry-Perot (FP) interference filter that can be spatially tuned utilizing a simplified fabrication process. The dielectric component of this filter is comprised of a thick silicon nitride (SiN) layer with 10 pairs of alternating SiN/SiO quarter wave layers surrounding this central layer, forming the FP resonator with the DBR mirrors terminating the cavity. The
spectral tuning mechanism is provided via a square lattice symmetry hole-array, with sub-wavelength individual elements, that is patterned onto the surface of this multilayer thin film stack, and transfer etched through the entire volume. Through variation of the hole-array parameters, the spectral transmission characteristics of the filter can be manipulated and tailored across the filter aperture surface.

### 2.1.1 Multilayer Dielectric Stack Contribution to Filter Performance

The evolution of this device into a wavelength dependent transmission filter began by initially looking at the broadband transmission stop band that is inherent in a DBR dielectric stack comprised of alternating high/low refractive index, quarter-wave dielectric layers. A defect layer (thicker high index layer) can then be incorporated into the middle of the stack to produce a narrow line-width transmission peak in the center of the transmission stop band. This essentially forms a FP filter with the DBR stacks on either side acting as the dielectric mirrors of the cavity, with the central layer designated as the cavity layer of the resonator. A plasma enhanced chemical vapor deposition (PECVD) process was used to grow the dielectric layers of the DBR stack. The characterization of this process entails quantification of the deposition rate of each film used as well as determining the optical properties of the film over the wavelengths of interest. An in detail overview of the STS PECVD tool used in this work as well as the optical characterization of the two thin film materials is provided in section 5.2.1. The following table summarizes the process parameters used in the PECVD of the dielectric thin film layers used in this work.
In terms of the multilayer dielectric stack component of the optical filter presented here, using the refractive index and deposition characterization information determined experimentally, 20 pairs of SiO/SiN quarter wave layers were grown, with the central high index SiN layer grown thicker to produce the desired transmission notch in the stop band of the wavelength dependent transmission stop band. The thickness of this central layer was set to a value such that only one single transmission peak was present within the stop band of the transmission spectrum over the wavelength region of interest. These 4” samples of optical transmission filters could easily be fabricated and used to benchmark RCWA simulation results. Using a Cary 500 Spectrophotometer, the optical transmission of the filter sample was measured over a 1200-1800 nm wavelength span. RCWA simulation results are overlaid on the measured
data and displayed below in Figure 2-2, for a 420 nm thick spacer SiN layer demonstrating a strong overlap between predicted and measured results.

Figure 2-2: RCWA modeling results overlaid on experimentally determined transmission characteristics of dielectric component of MOSSE structure

2.1.2 Nano-patterning/etching of Hole-array Contribution to Filter Performance

It is possible to tune the position of the transmission peak by changing the thickness of the defect layer. As mentioned previously, because the defect layer is in the middle of the stack, it is not possible to vary the spectral response of the device across the 4” wafer surface unless additional processing is performed on the defect layer before the top layers are deposited. One of our goals was to utilize a different spectral response tuning mechanism that can be integrated into the dielectric stack after it is grown and that can provide the ability to spatially vary the transmission response across the wafer surface. By etching square lattice hole arrays through the multilayer
dielectric stack, the fill factor can be adjusted to effectively position the transmission peak within the stop band to different locations since the position of the peak is dependent on the effective index that results from the patterning and etching of the hole arrays through the dielectric volume. The following figure depicts a rendition of the multilayer dielectric stack with a hole-array etched through the structure and an SEM image of a square lattice hole-array patterned via an electron beam lithographic process.

Figure 2-3: Spatially variant optical transmission filter MOSSE structure and SEM image of hole-array patterning/transfer etch over 2 cmx2cm area into multilayer dielectric stack.
In order to maintain a single transmission peak within the stop band, the lattice constant and hole diameters must be carefully decided upon during the design parameterization stage. The two tuning mechanisms that are exploited include keeping the lattice constant fixed and varying the hole diameter, and keeping the hole diameter fixed and varying the lattice constant of the patterned and etched hole arrays. These two mechanisms are easily exploited due to the logistics of the simplified fabrication process where all additional processing is done post-dielectric growth. The filter response can be tailored for a specific zone on the surface providing a mechanism to spatially vary the transmission spectral response across the surface of the filter by engineering the effective index of each zone based off of the hole-array parameters.

The first mechanism we targeted to provide spatial variation of the transmission response across the filter aperture entailed fixing the lattice constant of the hole-array while varying the hole diameter of the different arrays. Each array has fixed lattice constants, $\Lambda_x = \Lambda_y = 600$ nm, where the diameter of the individual hole elements in each array are 367 and 438 nm respectively. As we previously showed in [13], RCWA simulations have been performed to model the wavelength dependent transmission through filters of this type having these hole-array parameters. The following figure demonstrates the numerical results from the RCWA simulations depicting the ability to control the position of the transmission peak within the stop band by altering the hole diameter size of the individual arrays.
Figure 2-4: RCWA results demonstrating ability to position transmission peak within stop band through variation of hole diameter size of individual arrays.

From the above figure, it should be noted that the stop band is quite large, approximately 400 nm. For the 367 nm hole diameter array, the transmission peak is placed near 1520 nm, while the 440 nm hole diameter array places the transmission peak near 1480 nm. Thus, by altering the hole diameter of arrays with fixed lattice constant parameters, it is possible to provide a spatial variation of the optical transmission through the device.

The second tuning mechanism entails the variation of the lattice constant of the hole-arrays patterned and etched through the multilayer dielectric stack on different zones on the wafer surface to realize a space variant optical transmission filter. Fixing the hole diameter to a value of 370 nm, variation of the lattice constant of a patterned and etched zone on the filter surface results in a shift in the peak transmission wavelength location within the wide stop band.
between the different zones. Thus, the filter response can be tailored for a specific zone on the surface by varying the lattice constant of the hole array within each particular zone. Using this mechanism, over a certain range of lattice constant values for a particular hole diameter, the amount of shift of the transmission notch is related to the variation of the lattice constant of the hole arrays. In order to generate a 1st order approximation for the primary characteristics of the filter, it is necessary to quantify the effect of the hole arrays etched through the dielectric volume in terms of the effective index of the spacer layer. Through the use of a RCWA modeling routing to determine the effective index of the spacer layer as a function of the lattice constant, within the range previously specified, each particular hole array zone can parameterized in terms of the spacer layer effective index as a function of the lattice constant. This was done yielding the following relationship between the effective index of the spacer layer, $n_{\text{spacer,eff}}$, and the lattice constant, $\Lambda$, of the hole arrays in the different zones.

$$n_{\text{spacer,eff}} (\Lambda) = (2.5 \times 10^{-5}) \Lambda + 1.89$$ \hspace{1cm} (2.1)

This formulation for the effective spacer refractive index can be input into equation 1.5 to generate a 1st order approximation for the location of the transmission notch within the stop band that is a function of the lattice constant for each zone on the wafer.

$$\lambda_{\text{T_{x,peak}}} (\Lambda) = (0.02) \Lambda + 1512 \quad [\text{nm}]$$ \hspace{1cm} (2.2)

For lattice constants between 400 and 900 nm, this 1st order approximation correlates well with results obtained using RCWA tools as depicted in the following figure. This allows for a preliminary back of the envelop design of this type of filters, but in order to more precisely determine the peak transmission peak locations, a 2nd order curve fit is more applicable and is also presented in the following figure.
\[ \lambda_p = (1517.84) - (0.0015 \Lambda) + (1.791E-5 \Lambda^2) \]

Figure 2-5: 1st order model, 2nd order curve fit, and RCWA predictions of peak transmission location as function of lattice constant of hole array with constant hole diameter of 370nm.

2.2 Fabrication Process Flow

As alluded to previously, by maintaining a sequential fabrication process flow, the multilayer thin film deposition process is performed without interruption using this approach. As discussed in section 1.1.1, other conventional approaches to the realization of narrow band optical
transmission filters require additional processing at intermediate stages within the overall dielectric deposition process. The fabrication process flow for the MOSSE structure here is comprised of three, de-coupled, main fabrication stages: PECVD of multiple thin film stacks, e-beam lithography, and transfer etching. Each stage is performed in its entirety, allowing for the entire process flow to be performed sequentially and negating any troublesome planarization, delaminating, or structural compromising effects that arise with intermediate processing.

### 2.2.1 Process Flow Overview

A process flow diagram is provided as follows outlining this sequential fabrication process flow. Following the dielectric multilayer stack deposition onto the substrate wafer surface, a 100 nm chrome layer has to be deposited onto the surface in order for electron beam lithography to be used to pattern the hole-array pattern onto the surface. A layer of ZEP-520A [52] is then spun onto the surface of the metalized dielectric stack and exposed using the e-beam in a flash and repeat format.

![Process Flow Diagram](image)

**Figure 2-6: Fabrication process flow for MOSSE Tx filter**
In order for these nano-patterns to be transferred into the chrome layer to serve as an etch mask, a commercially available wet etching chemistry [54] is used followed by a DI H2O rinse. The transfer etching of the hole arrays into the multilayer dielectric stack was performed using an ICP/RIE etcher operated using a CHF3 chemistry, where the process is summarized in Table 2-1.

Table 2-2: Dry etching parameter summary

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICP Power</td>
<td>1000 W</td>
</tr>
<tr>
<td>RIE Power</td>
<td>500 W</td>
</tr>
<tr>
<td>CHF3 Gas Flow</td>
<td>50 sccm</td>
</tr>
<tr>
<td>O2 Gas Flow</td>
<td>5 sccm</td>
</tr>
<tr>
<td>Pressure</td>
<td>10 mTorr</td>
</tr>
</tbody>
</table>

2.2.2 Thin Film Characterization

The filter design requires 10 pairs of alternating, SiN/SiO, quarter wave thickness layers on either side of a thicker SiN central spacer layer. In order to deposit dielectric layers of certain thicknesses to meet design specifications, it was necessary to characterize the deposition rate for both SiO and SiN materials as well as perform an optical characterization of the refractive index at wavelengths of pertinence to determine the correct quarter-wave thicknesses. The refractive index at a wavelength of 1550 nm was determined to be 1.9360 and 1.4496 for the SiN and SiO thin film dielectric layers. The deposition rate for SiO is much higher than for the SiN deposition, and is cited previously in Table 2-1. Reference section 5.2.1, where a more detailed overview of this PECVD process and characterization process is provided. The wavelength dependent refractive index, over a wavelength range spanning from 200-1600 nm, is depicted in the following figure where the red curve and blue curve represent the SiN and SiO films respectively. Index of refraction values from 200-1000 nm were experimentally determined.
using an n and kappa analysis tool, where the 1000-1600 nm wavelength range of values comes from the curve fitting routine summarized in section 5.2.1.

![Graph of refractive index vs. wavelength for SiO/SiN films.](image)

**Figure 2-7: Optical characterization of refractive index of SiO/SiN films.**

Having determined the deposition rate and refractive index at wavelengths of pertinence for the two dielectric materials, the dielectric component to this MOSSE structure can be deposited to match design specifications.
2.2.3 Patterning of Hole-array utilizing Proximity Effect

In order to pattern hole-arrays onto the surface of the dielectric stacks and transfer etch them through the entire dielectric volume, 120 nm of electron evaporated chrome was deposited on the surface of the dielectric stacks. This metal layer serves two functions, firstly, to provide a charge release layer for the electron beam lithography, and secondly, to serve as a hard mask for the dry transfer etching of the hole-arrays. The ability to pattern hole-arrays utilizing electron beam lithography is supplemented in section 5.1.3. As described there, the proximity effect [35] was taken advantage of to efficiently pattern the hole-arrays using electron beam lithography. After spinning on a 375 nm thick layer ZEP-520A [52] to the metalized sample surface, the electron beam pattern generating system (EBPGS) [53] is operated in a single shot exposure fashion, taking advantage of the inherently circular nature of the electron beam itself. A write file effectively lays out a target grid mapped to the surface of the sample where the distance between the targets corresponds to the lattice constant of the square symmetry hole-array being patterned. This target grid is input to the EBPGS, and in a step and flash exposure routine, the hole-array can be patterned into the photoresist layer. Through characterization of the trade-off between electron beam size, beam step size, dose, and hole diameter, it is possible to generate these hole-arrays on the surface of the metallized dielectric stacks with diameters ranging from 100 – 600 nm. Figure 2-8 displays 3 different zones patterned with a 200 nm beam, 20 nm beam step size, and doses of 1500, 1600, and 1700 µC/cm², demonstrating the increase in hole diameter size as the dose is increased. It should be noted that with this exposure technique, variability in surface uniformities will affect the hole diameter size, but not affect the lattice constants of the hole-array pattern.
Figure 2-8: SEM images of nano-structured hole-arrays as dose increases from 1500 to 1700 µC/cm².

2.3 Experimental Test Data

2.3.1 Spatial, Spectral Transmission Characterization

The following figure depicts a fabricated 2 cm x 2 cm filter sample and SEM images of two different zones on a 4” wafer patterned with hole diameters corresponding to 367 and 438 nm respectively with lattice constants, $\Lambda_x = \Lambda_y = 600$ nm, fixed.

Figure 2-9: (a) Fabricated and diced Tx filter: 2 cm x 2cm sample (b) and (c): SEM images of two different zones on 4” sample patterned with 367 and 440 nm hole diameters
On this one single 4” wafer sample, two different zones were patterned and etched with hole diameters corresponding to 367 and 440 nm using the previously characterized data relating the e-beam dose to hole diameter for the 100 nA beam. It should be noted that in the transfer etching of the arrays through the dielectric volume, because of passivation effects and dilution of the chemistry during the etching process, the hole diameter may decrease as the array is transferred deeper into the dielectric stack. As the feature size of the holes decreases, this amount of hole taper increases. The Cary 500 spectrophotometer was used to optically characterize the two zones on the 4” wafer sample at near normal angle of incidence. The following figure depicts the optical transmission response of the two different zones on the 4” wafer patterned and etched with different square lattice hole diameter arrays.

Figure 2-10: Experimental data for filters with two different hole diameter arrays patterned on single 4” wafer.
In comparing the shift in the spectral response depicted in Figure 2-4 and Figure 2-10, two different effects must be considered in order to compare filter structures being modeled and filters fabricated. As the angle of incidence increases away from the normal, the position of the transmission peak shifts to shorter wavelengths. The second effect to consider originates from the finite amount of taper that is characteristic of each zone on the filter wafer sample. The difference between the predicted and measured locations of the transmission peaks for both zones can be attested to the near-normal angle of incidence during testing and the tapering effect. Through numerical modeling, the amount of taper for the 367 and 440 nm hole diameter arrays was found to be approximately 0.19° and 0.06° respectively.

The second tuning mechanism was investigated for 3 different lattice constant values. The following figure depicts SEM images of 3 different zones patterned and etched on a single 4” wafer with a constant hole diameter of 370 nm and lattice constants of 600, 700, and 800 nm.

![SEM images of 3 zones on 4” wafer sample patterned and etched with different lattice constants.](image)

In order to spectrally characterize each of the three zones containing hole arrays with lattice constants of 600, 700, and 800 nm, an incident 380 µm diameter collimated beam pigtailed to a tunable laser was mapped and aligned to the filter, fixing the optical axis of the beam to be perpendicular with the surfaces of all four patterned zones. The thickness of the spacer layer was
chosen according to equation 1.5 to be 400 nm, resulting in a peak transmission peak located at a wavelength of 1548.8 nm. Each respective zone was illuminated with a normally incident collimated beam with a secondary collimator aligned to the backside of each patterned zone to collect the transmitted light as the source was swept from 1540 – 1570 nm. Operating at an optical power of 2.5 dBm, the wavelength of maximum transmission was identified for each of the three zones on the wafer. The theoretically predicted transmission characteristics of each zone were also analyzed utilizing RCWA to investigate the relationship between the lattice constant of each zone and the peak transmission wavelength. In comparing each scenario, the filter demonstrated the same 0.02 nm shift in the transmission peak for every nano-meter variation in lattice constant. The discrepancy between the experimental performance and that predicted using a RCWA formulism is due to the assumption made in modeling the filter where there is no variation in the hole diameter as the patterned hole arrays are transfer etched through the dielectric stack. In fact, in order to predict the transmission response of a particular zone on a fabricated filter, the tapering effect that occurs during the transfer etch of the hole arrays into the dielectric stack has to be taken into consideration. The degree of taper in samples fabricated here were estimated through a combination of numerical modeling and laboratory experimentation and found to be approximately 0.15°. This amount of tapering that occurred during the transfer etching process was incorporated into our models and depicted in the following figure overlaid with the measured wavelength dependent transmission response of the three zones of interest on the wafer. Each zone demonstrated approximately 74% transmission for the respective transmission peak corresponding to each patterned zone on the wafer.
Figure 2-12: Experimental transmission as function of wavelength overlaid with predicted transmission response incorporating a 0.15° of tapering into RCWA model.

This technique for fabrication of a space variant optical transmission filter is unique in that the processes for patterning and etching are constant for each zone containing hole arrays of different lattice constants, the only thing that changes is the write file for the electron beam lithography adjusting the lattice constant of the targets for the single shot exposures. This simplified fabrication process facilitated realistic analytical performance predictions incorporating hole tapering effects incurred during etching processes allowing for the verification of device performance.
2.4 Transmission Peak Spectral Line-width

As in the case of conventional dielectric based Fabry-Perot transmission filters, the cavity mirror reflectivity, and ultimately the finesse of the overall resonator, determine the overall line-width of the transmission peak within the stop band of the transmission spectrum. In the case of the MOSSE transmission filter, this can be investigated in terms of the number of pairs of SiN/SiO layers used to create the DBR reflectors on both sides of the central SiN layer, keeping in mind that this MOSSE filter utilizes a tuning mechanism based on effective index variation from control over the fill factor.

As done to produce equation [2.1], as the number of dielectric layers of the DBR sections is varied, it is necessary to take into account the resultant variation in effective index when comparing structures with the same hole array parameters, but different number of layers comprising the terminating DBR multilayer stacks. The following RCWA modeling results were obtained taking into account the effective index variation that occurs due to the addition of more pairs of DBR layers on both sides of the resonator cavity. In doing so, the location of the transmission peaks is maintained at the same wavelength location as the number of pairs of DBR mirrors that surround the central SiN layer is varied. This allows for a quantification of the line-width as a function of the number of pairs of DBR layers on both sides of the SiN central layer.
Figure 2-13: RCWA results for transmission peak line-width spectrum as function of # DBR pairs.

From the figure, increasing the number of DBR pairs from 20, as in the MOSSE filters presented here, to 32 pairs, enhances the transmission peak line-width from 2.4 nm to 0.24 nm. Using the effective index parameterization used in this analysis with further RCWA modeling to determine the reflectivity from the individual DBR multilayer stacks with a specific number of high/low refractive index layer pairs, provides suitable parameterization to generate a 1st order model for the line-width as a function of the # pairs of DBR layers.

The effective reflectivity, $R_{\text{eff}}$, as a function of the # of pairs of layers that comprise the DBR mirrors terminating the central SiN layer determined through RCWA simulations is displayed in the following graph.
From equation 1.1, it follows that from the equations for finesse and free spectral range (FSR), the FWHM of the resonance peak in terms of wavelength can be expressed as shown in the equation that follows.

\[ \Delta \lambda = \frac{\lambda_0^2}{2 \pi n_{\text{spacer}} d_{\text{spacer}}} \frac{1 - R_{\text{eff}}}{\sqrt{R_{\text{eff}}}} \]  \hspace{1cm} 2.3

From Figure 2-14, the relationship between \( R_{\text{eff}} \) and (# of DBR pairs) can be used in conjunction with this equation and the appropriate effective index value for the spacer layer thickness and hole array parameters etched through the layer volume to generate a 1st order approximation for the transmission peak line-width. The following figure depicts both RCWA (tracked from

*Figure 2-14: \( R_{\text{eff}} \) of DBR stacks as function of # pairs of layers that make up mirror.*
Figure 2-13) and 1st order model determined line-width as a function of the # of DBR pairs used in the filter structure.

Figure 2-15: Transmission peak line-width as function of # DBR pairs RCWA (red) and 1st order model (blue)

2.5 Angle of Incidence Dependence on Transmission Response

It is important to consider filter performance under variation of the angle of incidence of the field incident to the filter surface away from the normal. Consider the MOSSE transmission filter structure with 20 pairs of quarter-wave DBR layers surrounding the central SiN cavity layer and hole array parameters of 370 nm hole diameter and lattice constants of 600 nm. The spectral transmission characteristics of this filter are provided in Figure 2-4, where the transmission peak
is located within the stop band near a wavelength of 1520 nm under normally incident conditions. As with all Fabry-Perot type transmission filters, the transmission peak wavelength location is strongly a function of the angle of incidence and effective index of the central spacer layer. Assigning a cut-off threshold for transmission efficiency at 65 %, this type of MOSSE filter was observed through RCWA simulations to perform within these performance specifications up to a 15° angle of incidence. These results are presented in the following figure where the angle of incidence of the plane wave incident to the filter is increased away from normal up to 15°.

![Figure 2-16: Transmission spectrum as function of plane wave angle of incidence](image)

Figure 2-16: Transmission spectrum as function of plane wave angle of incidence

As can be deduced from the figure above, as the angle of incidence is increased away from the normal, the transmission peak wavelength location within the stop band shifts to shorter
wavelengths. After an angle of incidence value of 24° is exceeded, the transmission efficiency associated with the transmission peak drops below 55%.
3 CHAPTER III: SPATIALLY POLARIZING AUTO-CLONED ELEMENTS (SPACE)

The MOSSE presented in this section provides another level of progression in the previously demonstrated GaAs based PCE technology [19,88] for infra-red wavelengths utilizing a low refractive index, dielectric based structure with feasible feature sizes and aspect ratios compatible with present lithographic and transfer etching capabilities. This approach to PCE technology addresses two critical issues that were observed when realizing the GaAs based PCE device, both of which originated from the material properties of the substrate used to fabricate the device within. As mentioned in the introduction section, from effective index theory [21], it has been observed that for a binary, sub-wavelength grating, the depth of the grating required to achieve a $\pi$-phase retardation decreases as the refractive index of the material increases. However, the relationship between refractive index and Fresnel reflection losses must also be considered. With this approach, materials have to be chosen that result in grating depths and aspect ratios that are realizable with available lithographic and transfer etching tools. For the GaAs based PCE structure, the necessary grating aspect ratio for $\pi$-phase retardation of 2.57:1 was realizable fabrication wise, due to the relatively high refractive index of GaAs, but the device performance suffered from a high amount of Fresnel reflection loss. Using this approach, by moving to a set of materials that possess lower refractive index values over the wavelengths of interest to reduce the reflectivity loss issues, the required aspect ratios can exceed 100:1.

The MOSSE-SPACE component discussed here takes advantage of the low refractive index of SiO$_2$ and SiO/SiN thin films to produce a low reflectance structure that allows for the high transmission efficiency while providing an optimized amount of birefringence. This is accomplished using an auto-cloned form birefringent structure [45-47] by auto-cloning lower index material onto a low aspect ratio binary substrate template structure in SiO$_2$. Under specific
growth process conditions, multilayer thin film deposition upon the surface of a binary template results in an evolution in the template surface topography, morphing the cross-sectional surface geometry from square to triangular. The lower refractive index material and triangular surface profile enables these SPACE components to obtain a high level of birefringence without sacrificing transmission efficiency.

### 3.1 Component Description

The SPACE component described within this section utilizes low index dielectric materials to provide high transmission and low reflectivity, where the resulting structure possesses a high effective aspect ratio due to the multilayer thin film component of the structure in order to provide an optimized amount of birefringence [14,15]. In addition, the triangular topography of the resulting SPACE component provides the optimal geometry for minimal reflection from the effective grating structure [10]. A rendition of the SPACE component discussed here is provided below in the following figure utilizing the string method [27-29, 48,20]. This method has been shown [105] to provide the ability to efficiently simulate the multiple physical processes involved in a multiple thin film deposition process upon a binary substrate template to describe the evolution of the surface.
3.1.1 Binary, Continuous Template Design Description

In order to describe the operation of the SPACE components presented here, the overall structure is discussed in terms of its two main components, namely, the binary template and auto-cloned multilayer growth components. The template design is based on the continuous grating layout based PCE devices that were addressed in [13], where any desired output polarization state could be created by engineering the orientation of the form-birefringent element design spatially with respect to the incident linearly polarized field. The linear polarization to azimuthal/radial
polarization converting element has a grating vector function described as follows where $K_o$ is in terms of the spatial period, $K_o = 2\pi / \Lambda (r, \theta)$.

\[
\vec{K}(r, \theta) = K_o (r, \theta) [\sin (\frac{\theta}{2}) \hat{r} + \cos (\frac{\theta}{2}) \hat{\theta}] \tag{3.1}
\]

A differential equation governing the behavior of this grating function can subsequently be generated by applying the grating continuity constraint, $\nabla \times \vec{K} = 0$, to maintain continuity of the grating. This equation can be further simplified under the assumption that $K_o$ has no azimuthal dependence. Under this pretense, it is thus possible to generate a 1st order linear differential equation defining the grating vector function as follows having applied the grating continuity constraint.

\[
\frac{\partial}{\partial r} K_o (r) + \frac{1}{2r} K_o (r) = 0 \tag{3.2}
\]

The solution to this linear first order differential equation can be substituted back into the equation for the generalized grating vector function in the form:

\[
\vec{K}(r, \theta) = \frac{2\pi}{\Lambda_0} \sqrt{\frac{r_o}{r}} \left[ \sin (\frac{\theta}{2}) \hat{r} + \cos (\frac{\theta}{2}) \hat{\theta} \right] \tag{3.3}
\]

This grating vector function is related to the phase function, $\phi (r, \theta)$, of the grating through, where the grating vector function is equal to the gradient of the grating phase function as shown below.

\[
\nabla \phi (r, \theta) = \frac{2\pi}{\Lambda_0} \sqrt{\frac{r_o}{r}} \left[ \sin (\frac{\theta}{2}) \hat{r} + \cos (\frac{\theta}{2}) \hat{\theta} \right] \tag{3.4}
\]

Through separation of radial and azimuthal polarization components that result from the gradient operation, two 1st order linear differential equations can be written as follows.
\[
\frac{\partial \phi}{\partial r} = K_0(r) \sin\left(\frac{\theta}{2}\right) \tag{3.5}
\]

\[
\frac{1}{r} \frac{\partial \phi}{\partial \theta} = K_0(r) \cos\left(\frac{\theta}{2}\right) \tag{3.6}
\]

Both of these differential equations have straightforward solutions, where the overall grating phase function solution is the addition of each individual solution. This phase function can now be written as:

\[
\phi(r, \theta) = \frac{8 \pi r_0}{\Lambda_0} \sqrt{\frac{r}{r_0}} \sin\left(\frac{\theta}{2}\right) \tag{3.7}
\]

This phase function projected into the substrate forms the binary template which serves as the foundation of the SPACE structure for subsequent auto-cloning multilayer thin film deposition process. This phase function can be synthesized into a file format compatible with available lithography systems in order to pattern a photoresist coated substrate, and is depicted in the following figure.
Figure 3-2: Pattern used in e-beam lithography for binary template fabrication.

This template for the SPACE structure is comprised of the phase function etched into a low index, fused silica substrate to a depth where the maximum aspect ratio is no greater than 2.5:1. With sub-wavelength features at these depths in a low index substrate material, this structure alone does not provide the necessary amount of birefringence necessary for a $\pi$-phase retardation. The auto-cloned multilayer thin film component of this SPACE structure combined with this binary template is the mechanism by which the overall SPACE structure is able to provide the required amount of birefringence.
3.1.2 Multilayer Deposition and Birefringence Optimization

The auto-cloning multilayer thin film component to the SPACE structure has been investigated in terms of the specific geometric and material parameters of the dielectric thin film layers required to provide an optimized amount of birefringence. Due to the dielectric thin film materials available and fundamental effects of the multilayer dielectric deposition process on the topography of the binary template that is inherent in the auto-cloning process, several SPACE structural parameters are fixed and not included in the optimization routine. Because the template is comprised of 50 % duty cycle binary patterns, after deposition, the final SPACE structure will have a triangular topography with a duty cycle of 50% as well, where the slopes of the surface profiles are also fixed due to the physics of the auto-cloning process itself. The chosen dielectric material set for this SPACE structure consisted of two materials, SiO and SiN, thus fixing the refractive index parameters as well at values of 1.4458 and 1.9767 respectively. Thus, the only parameter that is not fixed and is incorporated into our optimization of the overall structure birefringence is the physical layer thicknesses of the alternating SiO and SiN dielectric layers. These layer thicknesses can be described in terms of the longitudinal period and duty cycle, $\Lambda_z$ and $f_z$ as depicted in the inset of Figure 3-3 where the device on the right was generated using the string method as performed in [25]. The degree of birefringence, $\Delta n$, is presented as a function of the longitudinal duty cycle and period, where the longitudinal period was scaled relative to the lateral period, $\Lambda_x$. 
Figure 3-3: Birefringence of SPACE device in terms of film thicknesses and longitudinal duty cycle.

From this figure, there is an obvious and dramatic increase in the birefringence as the layer thicknesses become as thin as possible. Essentially, it can be deduced that in order to provide maximum birefringence, the SiO and SiN layers should be of equal thicknesses and as thin as possible. The thickness of the layers is determined by the process parameters of the particular dielectric deposition process in order to maintain a high level of uniformity, low mechanical stress (no intermediate annealing steps are required), and repeatable film thickness layers.
3.2 Fabrication Process Flow

The overall fabrication process for these SPACE devices can be decoupled into two different process development phases. The first phase involves the patterning and transfer etching of the template grating phase function, described in equation 3.7, into a 4” SiO2 substrate wafer. The second stage involves the auto-cloning PECVD of multiple thin film layers on top of the fabricated templates. As with the MOSSE structure presented in the previous chapter, the SPACE fabrication process is sequential and the lithographic/transfer etching stages of the process flow are separated from the thin film deposition process stage.

3.2.1 Template Process Flow Overview

The following figure depicts a basic fabrication process flow for the patterning and transfer etching of the grating phase function into the binary template of the SPACE component.

![Fabrication process flow for PCE binary SiO2 substrate template.](image)

Figure 3-4: Fabrication process flow for PCE binary SiO2 substrate template.
The SiO₂ template substrate is prepared for electron beam lithographic patterning of the grating phase function by initially coating a chrome charge release/etch mask layer. Using ZEP-520A as the positive electron beam photoresist, e-beam lithography is used to pattern the phase function into the photoresist layer. This pattern is subsequently transfer etched through the chrome layer, forming an etch mask for transfer etching of the pattern into the SiO₂ substrate material. ICP/RIE dry etching processes are utilized to transfer etch the chrome mask layer pattern into the fused silica substrate material.

3.2.2 Binary Template Dose Matrix Results

A summary of the parameters of the binary template grating parameters is provided in the following table. Over all grating periodicities, the duty cycle is fixed at a value of 50%.

Table 3-1: Summary of grating parameters within overall patterned and etched template area.

<table>
<thead>
<tr>
<th>PARAMETER DESCRIPTION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Period</td>
<td>400 nm</td>
</tr>
<tr>
<td>Maximum Period</td>
<td>740 nm</td>
</tr>
<tr>
<td>Etched Depth</td>
<td>400 nm</td>
</tr>
<tr>
<td>Minimum Aspect Ratio</td>
<td>1.081:1</td>
</tr>
<tr>
<td>Maximum Aspect Ratio</td>
<td>2:1</td>
</tr>
<tr>
<td>~ Total Patterned Area</td>
<td>~ 2mm x 2mm</td>
</tr>
</tbody>
</table>

The first stage in the fabrication process for the template entails coating the 1 mm thick SiO₂ wafer with a 100 nm chrome layer via a Temescal electron beam evaporation system. This layer will serve dual purposes, first as a charge release layer for the subsequent electron beam
lithographic patterning of the resist layer, and second, as a hard mask for the transfer etching of the pattern into the substrate. Once the chrome layer has been deposited onto the SiO$_2$ substrate, a 300 nm layer of ZEP-520A, a positive e-beam photoresist, was spun onto the surface at a spin speed of 5000 rpm. The pattern depicted in Figure 3-2 was lithographically transferred into the photoresist layer using a Leica 5000+ electron beam writing system. A functional overview of this particular electron beam writing system and significant figures of merit are provided in section 5.1.3.

Operating the tool using a 100 nA/50 kV beam, a dose matrix was performed in order to determine the optimal dose that would accurately replicate the design feature sizes and maintain vertical side walls. Doses ranging from 80-150 $\mu$C/cm$^2$ were used to pattern binary patterns ranging from with periodicities ranging from 400 nm to 1000 nm in order to encompass the entire range of periodicities that our SPACE component contains in order to verify the dose to clear criteria for each specific dose via line width measurements under the SEM. After exposure, the following figure depicts an e-beam dose of 110 $\mu$C/cm$^2$ where the binary patterns were all dose to clear and of the proper geometrical dimensions.

![SEM images of etched SiO2 binary patterns using optimized e-beam dose](image)

Figure 3-5: SEM images of etched SiO2 binary patterns using optimized e-beam dose
Knowing the dosage required for a particular beam on the Leica e-beam lithography system necessary for dose to clear patterning of binary features onto a surface coated with 100 nm of chrome, allows for the patterning of the phase pattern into a photoresist/chrome coated wafer for lithographic phase of the template fabrication. Once this patterning has been complete, the pattern is developed in ZEP-RD for 90 seconds followed by a 30 second rinse in IPA and hard bake at 180°C for 90 seconds. Since this pattern will be subsequently transferred into the chrome masking layer, a brief 10 second oxygen descum was then performed to ensure that all sectors of the lithographically patterned area satisfy dose to clear criteria. The sample was then immersed in a chrome wet etching chemistry in order to transfer the grating structure into the chrome hard mask layer. An optical microscope operated under dark-field illumination conditions allowed for the evaluation and identification of the amount of wet etching necessary to clear the patterns. For these SPACE components, a total wet etching time of 75 seconds, followed by a DI H₂O rinse, was seen to be adequate in the transferring of the lithographic pattern into the hard mask layer. The remaining photoresist was then removed using methylene choride solution and an IPA rinse, followed by a piranha wet chemical clean to ensure all organics were completely removed from the template surface. Using a CHF₃ chemistry in conjunction with an inductively coupled plasma etcher, the chrome masking layer pattern can be transfer etched into the substrate surface. The following table summarizes the main figures of merit as related to the etch process used in the template fabrication.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICP Power</td>
<td>1000 W</td>
</tr>
<tr>
<td>RIE Power</td>
<td>500 W</td>
</tr>
<tr>
<td>CHF₃ Gas Flow</td>
<td>50 sccm</td>
</tr>
<tr>
<td>O₂ Gas Flow</td>
<td>5 sccm</td>
</tr>
<tr>
<td>Pressure</td>
<td>10 mTorr</td>
</tr>
</tbody>
</table>
In order to verify the etch rate of this particular recipe, test samples were fabricated on SOI wafers since the oxide layer thickness is much thinner than the buried Si layer, thus cleaving and cross sectional metrology of final structures are possible. The etch process was performed on these samples, etching for a total time of 2 minutes and 15 seconds followed by a 30 second oxygen descum process. Using an Alpha-step profilometer on openings in the chrome layer at alternate locations on the same sample, it was verified that approximately 90 nm of chrome was remaining post dry etching. The following SEM images depict a surface view of a patterned and etched SPACE template, and a cross sectional verification that the etching time provided an etch depth of 400 nm (subtracting 90 nm of chrome mask layer thickness remaining). It should be noted that in these samples, the chrome masking layer has not yet been removed from the template surface.

Figure 3-6: SEM images of top surface of binary SiO$_2$ template (a) top view of vortex center (b) cross-section of etched template with chrome mask remaining.
3.2.3 PECVD Auto-Cloning Processing

The second stage to the overall SPACE component fabrication entails utilizing an auto-cloning multilayer dielectric deposition process performed onto the surface of the SiO$_2$ templates using a plasma enhanced chemical vapor deposition (PECVD) tool. For these devices, an STS PECVD tool was used at the Georgia Tech MIRC fabrication facilities, which required a similar optical thin film characterization as performed for the spatial filter work. This characterization is presented in section 5.2.1 for this specific deposition tool. The following table summarizes the process parameters used and in this multilayer deposition work.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiN Deposition Showerhead Temperature</td>
<td>250 °C</td>
</tr>
<tr>
<td>Platten Temperature</td>
<td>300 °C</td>
</tr>
<tr>
<td>Pressure</td>
<td>900 mTorr</td>
</tr>
<tr>
<td>N2 Gas Flow</td>
<td>1910 sccm</td>
</tr>
<tr>
<td>100% SiH4 Gas Flow</td>
<td>36 sccm</td>
</tr>
<tr>
<td>NH3 Gas Flow</td>
<td>52 sccm</td>
</tr>
<tr>
<td>Power</td>
<td>20 W</td>
</tr>
<tr>
<td>Load %</td>
<td>0.52</td>
</tr>
<tr>
<td>Tune %</td>
<td>0.51</td>
</tr>
<tr>
<td>Deposition Rate</td>
<td>7.394 nm/min</td>
</tr>
<tr>
<td>SiO Deposition Showerhead Temperature</td>
<td>250 °C</td>
</tr>
<tr>
<td>Platten Temperature</td>
<td>300 °C</td>
</tr>
<tr>
<td>Pressure</td>
<td>900 mTorr</td>
</tr>
<tr>
<td>N2 Gas Flow</td>
<td>390 sccm</td>
</tr>
<tr>
<td>100% SiH4 Gas Flow</td>
<td>10 sccm</td>
</tr>
<tr>
<td>N2O Gas Flow</td>
<td>1410 sccm</td>
</tr>
<tr>
<td>Power</td>
<td>30 W</td>
</tr>
<tr>
<td>Load %</td>
<td>0.52</td>
</tr>
<tr>
<td>Tune %</td>
<td>0.51</td>
</tr>
<tr>
<td>Deposition Rate</td>
<td>49.034 nm/min</td>
</tr>
</tbody>
</table>

OVERALL PROCESS SUMMARY

- Total # of Pairs: 32
- SiO Thickness: 125 nm
- SiO Refractive Index @ 1550 nm: 1.446
- SiN Thickness: 125 nm
- SiN Refractive Index @ 1550 nm: 1.977
- Lπ thickness: 8.4 μm
It should be noted that due to the low mechanical stress properties of the thin films deposited with the STS PECVD tool, overall dielectric stack thicknesses of 8 µm are possible without the necessity to perform additional annealing steps at intermediate stages within the overall dielectric deposition process. SEM metrology was performed on final SPACE structures post dielectric deposition in order to demonstrate the triangular topographical characteristics of the device. These images are provided in the following figure taken with a Hitachi SEM operated at 5 kV. Surface roughness that is evident was contributed to by a 30 nm Au sputtered layer that was required to deposit on the surface of the SPACE device to serve as a charge release layer for the SEM metrology.
Figure 3-7: SEM images of top surface of SPACE-based PCE device demonstrating triangular topography resulting from multilayer auto-cloning deposition process onto binary template substrate.

3.3 Experimental Test Data

The SPACE has been experimentally characterized in terms of functionality and efficiency. First, having conditioned an incident beam to provide a collimated, linearly polarized beam, normally incident to the SPACE structure, the ability to convert this beam into a purely
azimuthally polarized beam is verified. With this output polarization state characterized, the transmission efficiency is also quantified in the following data results.

### 3.3.1 Experimental Verification of Linear to Azimuthal Polarization Conversion

The optical characterization of the SPACE device was performed utilizing an Agilent Tunable Laser Source and Detector module to provide a stable 1550 nm input source. This source is coupled to a single mode fiber (SMF) output, and was operated at an output power of 2 mW. In order to provide a collimated input into the characterization setup, the SMF output was pigtailed to a GRIN lens based fiber collimator that provided an output beam size of 380 µm (FWHM). The following figure depicts the experimental setup used to characterize the SPACE device where the output analyzer is removed for beam analysis using a phosphor coated CCD camera.

![Experimental setup for optical characterization of SPACE device](image)

Figure 3-8: Experimental setup for optical characterization of SPACE device
The total distance between the fiber collimator output facet and imaging plane is within the 2.35 cm throw distance of the collimator itself at a wavelength of 1550 nm. The input beam to the SPACE device needs to be conditioned such that only a linearly polarized beam is incident on the SPACE device. The thin film polarizer provides this functionality and adequately conditions the polarization of the input beam to the SPACE device. After defining an optical axis, the SPACE device is aligned to this beam projected onto a CCD camera. Post alignment, a purely azimuthal polarization distribution was observed at the output of the device. The analyzer was used to verify the azimuthal polarization state by rotating the analyzer and observing the rotating pairs of sectors that would comprise the entire azimuthal donut distribution. 90 degree rotation of the element around the optical axis resulted in a radially polarized output beam. Both the azimuthal and radial polarization outputs are displayed in the following figure.

Figure 3-9: SPACE component output beam demonstrating purely (a) radial and (b) azimuthal polarization distribution
3.3.2 Transmission Efficiency Characterization

Once the azimuthal polarization output was verified, power measurements were made throughout the optical system in order to characterize the transmission efficiency of the SPACE device. For the input power of 2.0 mW incident on the SPACE device, a high transmission efficiency of approximately 90% was measured in the azimuthally polarized output beam, containing a total power of 1.796 mW.

In this work, auto-cloning of multilayer dielectric thin film layers deposited on top of a low aspect ratio substrate template was utilized to create optimized form-birefringent elements with high transmission efficiencies of approximately 90%. The triangular topography characteristic of the auto-cloning mechanism performed on binary structures was observed through SEM metrology. Optical characterization of the element verified the high transmission efficiency of these SPACE devices as well as the purely azimuthally polarized beam at the output of the device for a linear polarization input beam. This device successfully addressed the reflectivity losses associated with the initial GaAs based approach through the combination of usage of low index materials as well as the inherent triangular topographical structures characteristic of the auto-cloning process on binary templates.
4 CHAPTER IV: SPECTRALLY SELECTIVE CAVITY MIRRORS

In this chapter, a spectrally selective optical element is introduced based on a 2-D guided mode resonance filter (GMRF) utilized as a cavity mirror that is transparent over the range of pump wavelengths used in this work. This GMRF provides a highly efficient, narrow line-width reflection for signal wavelengths that can be exploited in fiber laser resonators operated in an external cavity configuration. The combination of the ability to provide an efficient, narrow line-width, spectrally selective feedback within the gain bandwidth of the doped fiber structure and maintaining component transparency over pump wavelengths allows for the integration of these filters into fiber laser resonators facilitating convenient pumping schemes. As eluded to in the introduction section, by adopting the pumping/external cavity configuration used throughout this work, the relatively large signal beam incident on the GMRF also provides additional system performance benefits in comparison to convention FBG technology with respect to non-linear and thermal issues that arise during high power operation of fiber lasers in general. In the system characterization section that follows, these system highlights are discussed further and in more detail. This technique using an intracore Bragg grating has been fabricated and demonstrated in [102] where the FBG provided the high reflectance, wavelength selective feedback mechanism required of one end of the resonator cavity.

Single resonance feedback GMRF’s have been investigated with respect to the gain bandwidth supported by an erbium (Er\textsuperscript{3+})/Ytterbium (Yt\textsuperscript{3+}) doped double cladding optical fiber structure. This particular doping material set provides gain over a bandwidth that encompasses a wavelength range from approximately 1500 – 1600 nm. Based off of the gain distribution across this wavelength range, the GMRF’s with single resonance feedback were designed such that the
reflected spectrum was placed at a wavelength location that coincides with the region of maximum gain supported by the doped fiber structure from 1535 – 1555 nm.

In addition to this single resonance feedback GMRF element, further filter design was performed to exploit another convenient property of the filters themselves when utilized as spectrally selective feedback elements as made evident in [103]. In order to provide multiple wavelength feedback back into the fiber laser cavity, the authors utilized overlap-written FBG’s, with each grating used to provide more than 96 % reflectivity over an approximately 0.3 nm bandwidth. With this approach, a separate phase mask is required for each different UV-written grating. It is possible to design a single GMRF that provides multiple, narrow line-width reflection resonances. Because of the fabrication process utilized to fabricate these GMRF’s in this work, the wavelength selective feedback elements here can provide multiple resonance feedback without the necessity for multiple phase masks and fabrication alignment routines. A design for a dual wavelength GMRF (DW-GMRF) is provided in the sections that follow where the two resonances are placed at wavelength locations that coincide with maximum gain provided by the doped optical fiber structure.

Two different single resonance filter designs are fabricated using two different exposure tools, during the lithographic stage of the overall fabrication process flow. After optical characterization of the filters, one of the filters is utilized in an external cavity configuration fiber laser setup in order to provide wavelength selective feedback to the resonator within the gain bandwidth of the doped optical fiber structure.
4.1 Spectrally Selective Single Resonance Feedback Element

For the double cladding optical fiber laser (DCOFL) discussed here, the spectrally selective, single resonance, external feedback element used is a dual layer GMRF. The filter used in an external cavity DCOFL setup described here provides approximately 90 % reflection, with a line-width on the order of tens of nanometers for the core signal wavelength provided from the DCOF structure. The filter also maintains transparency over the span of wavelengths provided by the multimode pump module.

4.1.1 Component Description

As introduced in section1.2.2, GMRF’s operate under the principles of diffraction from a periodic structure and wave-guiding properties of a slab waveguide. Two different GMRF designs have been investigated, where the common design parameter between the two approaches involves using a SiN dielectric material as the wave-guiding layer, and SiO as the grating layer material. In both cases, the filters were required to fulfill two explicit requirements in order satisfy external cavity operation criteria for a specific pumping configuration that will be described in detail in the section that follows. The first requirement of the GMRF was to provide a narrow line-width, high efficiency reflectance at a wavelength located within the gain bandwidth of the DCOF structure used in the following work. The second requirement was dictated from the chosen pumping configuration, where the external, spectrally selective feedback element needed to be transparent over the wavelengths provided from the multimode pump module. These two different GMRF described in this work were designed, fabricated, and experimentally characterized, demonstrating the ability to satisfy the two requirements stipulated
above. The following figure depicts the basic geometry and structure of the dual layer GMRF’s presented in this work.

![Diagram of dual layer waveguide grating GMRF](image)

**Figure 4-1:** (a) Geometrical depiction of dual layer waveguide grating GMRF (cross-section) (b) hole array patterns for grating layer (surface view)

The grating layer in these filters consists of circular hole-arrays etched through the grating layer, stopping at the waveguide layer interface. Two different hole-array lattice symmetries, hexagonal and square, are explored, in order to demonstrate the ability to perform the lithographic stage of the GMRF fabrication process utilizing different exposure tools. The hexagonal and square lattice symmetry GMRF’s are lithographically patterned using a GCA stepper and Leica 5000+ EBPG system respectively. The two different options for lithography originate from the feature size of the circular elements that comprise the hole-array, which are larger for the hexagonal lattice symmetry than for square lattice symmetry. The following table
summarizes the main features of the two different designs of the GMRF’s where the geometric lattice constant parameters are defined in Figure 4-1.

<table>
<thead>
<tr>
<th>LATTICE SYMMETRY</th>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexagonal</td>
<td>Hole Diameter</td>
<td>800 nm</td>
</tr>
<tr>
<td></td>
<td>( \Lambda_x )</td>
<td>1150 nm</td>
</tr>
<tr>
<td></td>
<td>( \Lambda_y )</td>
<td>996 nm</td>
</tr>
<tr>
<td></td>
<td>SiN Refractive Index</td>
<td>1.936</td>
</tr>
<tr>
<td></td>
<td>SiN Layer Thickness</td>
<td>345 nm</td>
</tr>
<tr>
<td></td>
<td>SiO Refractive Index</td>
<td>1.4496</td>
</tr>
<tr>
<td></td>
<td>SiO Layer Thickness</td>
<td>230 nm</td>
</tr>
<tr>
<td>Square</td>
<td>Hole Diameter</td>
<td>450 nm</td>
</tr>
<tr>
<td></td>
<td>( \Lambda_x )</td>
<td>1000 nm</td>
</tr>
<tr>
<td></td>
<td>( \Lambda_y )</td>
<td>1000 nm</td>
</tr>
<tr>
<td></td>
<td>SiN Refractive Index</td>
<td>1.936</td>
</tr>
<tr>
<td></td>
<td>SiN Layer Thickness</td>
<td>200 nm</td>
</tr>
<tr>
<td></td>
<td>SiO Refractive Index</td>
<td>1.4496</td>
</tr>
<tr>
<td></td>
<td>SiO Layer Thickness</td>
<td>130 nm</td>
</tr>
</tbody>
</table>

4.1.2 Hexagonal/Square Lattice Symmetry Hole-Array Device Modeling

Rigorous Coupled Wave Analysis (RCWA) was utilized to predict the wavelength dependent reflection characteristics of the two proposed GMRF designs given the parameters summarized in the preceding table. For initial design purposes, it is assumed that the incident field onto the structure is normally incident, composed of planar, infinite wave-fronts.
In performing these simulations, three specific filter performance criteria were verified. First, the wavelength location of the reflection resonance must lie within the gain bandwidth of the DCOF which ranges from ~ 1500 – 1600 nm. This resonance must have a narrow line-width on the order of tens of nanometers. The second filter performance criteria that must be satisfied is that this resonance should correspond to a high level of reflection efficiency. The third criteria requires that the reflection response of the filters have no resonances within ± 7.5 nm on either side of the central wavelength of the spectrum supplied through the multimode diode array pump module, such that the filter is essentially transparent to the pump beam wavelengths.

For both cases of the HGMRF and SGMRF, RCWA simulations were performed to observe the wavelength dependent reflection characteristics over two different wavelength windows: 1530-1560 nm and 900-1000 nm. The following figure depict the RCWA simulation results for the two different filter designs, each observed over the two different wavelength ranges of interest. Line-width (FWHM) measurements of 0.15 and 0.17 nm are superimposed onto the peak reflection curves for both the HGMRF and SGMRF designs respectively.
From this figure, it is evident that both filter designs are capable of providing a high efficiency, narrow line-width reflection at a location within the gain spectrum of the DCOF, while maintaining transparency over the multimode pump module wavelengths. Both of these filter designs are compatible with the requirements for the external spectrally selective element utilized in the DCOFL external cavity optical system arrangement.
4.1.3 Dual Wavelength GMRF Design

A dual wavelength GMRF (DW-GMRF) was designed to provide wavelength selective feedback to the doped optical fiber structure at wavelength locations that coincide with maximal gain within the gain bandwidth supported by the dopant material set used. The following table summarizes the resultant design parameters for the DW-GMRF design based on a dual dielectric layer, hexagonal grating layout arrangement used in the single resonance design work.

Table 4-2: DW-GMRF Design Parameters

<table>
<thead>
<tr>
<th>PARAMETER DESCRIPTION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice Constant, a</td>
<td>1160 nm</td>
</tr>
<tr>
<td>Waveguide layer index, ( n_{HI} )</td>
<td>1.732</td>
</tr>
<tr>
<td>Waveguide layer thickness, ( d_2 )</td>
<td>400 nm</td>
</tr>
<tr>
<td>Grating layer index, ( n_{LO} )</td>
<td>1.4496</td>
</tr>
<tr>
<td>Grating layer thickness, ( d_1 )</td>
<td>230 nm</td>
</tr>
<tr>
<td>hole radius, ( r )</td>
<td>400 nm</td>
</tr>
</tbody>
</table>

RCWA analysis of the spectral reflectance behavior of this filter is provided in the figure that follows with the gain bandwidth of the doped-DCOF structure used is superimposed onto the figure.
Figure 4-3: Reflected spectrum from DW-GMRF structure with gain bandwidth of doped-DCOF superimposed onto figure.

4.2 GMRF External Element Fabrication/Characterization

The overall fabrication process for the external, spectrally selective GMRF’s can be decoupled into three different stages, the multilayer thin film deposition stage, the lithography stage, and the transfer etching stage. Due to the availability of different lithographic exposure tools, each with different printing resolution limits, the lithography stage of the GMRF’s was investigated two fold, using stepper and electron beam lithography technology to pattern the two different designs for high efficiency, narrow line-width filters with a peak reflections located within the c-band of wavelengths (1530 – 1565 nm).

4.2.1 Thin Film Deposition of Waveguide/Grating Dielectric Layers

In the preceding component description section, the dielectric component of the GMRF used in the DCOFL resonator cavity is comprised of two SiN/SiO dielectric layers deposited onto a
fused silica (SiO$_2$) substrate. A PECVD approach to the multilayer thin film deposition was used utilizing a STS Multiplex PECVD tool in conjunction with the appropriate gas chemistries and process parameters. For a more detailed overview of the tool and the optical characterization process of the SiN/SiO thin film used in this work, section 5.2.1. These gas chemistries and process parameters are outlined in the following table summarizing the PECVD SiN and SiO waveguide and grating layers respectively. The measured thicknesses of the SiN waveguide and SiO grating layers used in the HGMRF and SGMRF is also provided in this table.

**Table 4-3: Summary of PECVD process parameters.**

<table>
<thead>
<tr>
<th>Process</th>
<th>Parameter Description</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiN Deposition</td>
<td>Showerhead Temperature</td>
<td>250 °C</td>
</tr>
<tr>
<td></td>
<td>Platten Temperature</td>
<td>300 °C</td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
<td>900 mTorr</td>
</tr>
<tr>
<td></td>
<td>N2 Gas Flow</td>
<td>1910 sccm</td>
</tr>
<tr>
<td></td>
<td>100% SiH4 Gas Flow</td>
<td>36 sccm</td>
</tr>
<tr>
<td></td>
<td>NH3 Gas Flow</td>
<td>52 sccm</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>20 W</td>
</tr>
<tr>
<td></td>
<td>Load %</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Tune %</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Deposition Rate</td>
<td>9.897 nm/min</td>
</tr>
<tr>
<td></td>
<td>Refractive Index @ 1550 nm</td>
<td>1.936</td>
</tr>
<tr>
<td>SiO Deposition</td>
<td>Showerhead Temperature</td>
<td>250 °C</td>
</tr>
<tr>
<td></td>
<td>Platten Temperature</td>
<td>300 °C</td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
<td>900 mTorr</td>
</tr>
<tr>
<td></td>
<td>N2 Gas Flow</td>
<td>390 sccm</td>
</tr>
<tr>
<td></td>
<td>100% SiH4 Gas Flow</td>
<td>10 sccm</td>
</tr>
<tr>
<td></td>
<td>N2O Gas Flow</td>
<td>1410 sccm</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>30 W</td>
</tr>
<tr>
<td></td>
<td>Load %</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Tune %</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Deposition Rate</td>
<td>53.26 nm/min</td>
</tr>
<tr>
<td></td>
<td>Refractive Index @ 1550 nm</td>
<td>1.4496</td>
</tr>
<tr>
<td>Stepper Lithographic Process</td>
<td>SiN waveguide layer thickness</td>
<td>345 nm</td>
</tr>
<tr>
<td></td>
<td>SiO grating layer thickness</td>
<td>230 nm</td>
</tr>
<tr>
<td>E-Beam Lithographic Process</td>
<td>SiN waveguide layer thickness</td>
<td>200 nm</td>
</tr>
<tr>
<td></td>
<td>SiO grating layer thickness</td>
<td>130 nm</td>
</tr>
</tbody>
</table>
Again, the two different lithographic process approaches utilize different designs with different dielectric layer thicknesses and grating parameters. The dielectric thin film growth parameters remain consistent for both designs, while the lithography stage of the fabrication process is performed using two different exposure tools for each of the two designs.

4.2.2 HGMRF: Stepper Result

The hexagonal GMRF (HGMRF) design involves the use of a projection based G-line GCA stepper to perform the patterning of a substrate whose surface is coated with a planar layer of photoresist. There are several significant issues to address when using a stepper to pattern hole-arrays with feature sizes which are at the resolution limit of the exposure tool itself. Because the patterned features are to be subsequently transfer etched into the dielectric grating layer underneath, a G-line positive photoresist is required that coats at thicknesses around 800 nm (to maintain 1:1 aspect ratio for 800 nm diameter holes) in order to work within the dry etching selectivity (photoresist:SiN) requirements that determine the ability to transfer etch the hole-arrays into the SiN layer. S1805 positive photoresist is the resist chosen for this process which coats approximately 800 nm at a spin speed of 5000 rpm. Unfortunately, this photoresist does not provide enough absorption at this thickness for minimal exposures on the GCA stepper resulting in back reflections from the mounting chuck compromising the exposed patterns. This back reflection problem was alleviated through the addition of another fabrication process step where a 60 nm chrome layer was deposited on the surface of the SiO₂ wafer post multilayer thin film deposition. The ideal imaging conditions for feature sizes at the resolution limit of the GCA stepper entails an optimization of focus offset and dose parameters used in the exposure. This trade-off between focus offset and dose was investigated in terms of uniformity of feature sizes
and depths across the pattern die using a thinned version of the S1805 resist which allows for photoresist coatings of thicknesses of around 240 nm. We moved to a thinned version of the photoresist for two reasons, first to allow for the AFM probe to reach the bottom of the holes, and second to decrease the number of iterations necessary to experimentally determine the optimal values for focus offset and dose required for uniformity and dose to clear across the entire die. The following AFM image was taken of a dose to clear die demonstrating the printing of 700 nm diameter holes intentionally undersized from the design parameters to account for feature size enhancement that occurs during pattern transfer into chrome masking layer.

Figure 4-4: AFM image of thinned S1805 resist layer patterned using GCA Stepper

Using a wet chemistry, this pattern was transferred through the chrome masking layer in order to serve as a hard mask for the subsequent dry etching into the grating layer of the GMRF multilayer dielectric structure. The following AFM data image depicts the depth and surface information for the chrome masking layer with photoresist remaining.
Figure 4-5: AFM data of chrome masking layer with photoresist layer remaining.

The maximum uniform area using the GCA stepper, with the masking apertures completely opened, was a 1.4 cm square area pattern. The larger the area where the hole-arrays are patterned, lens aberrations become more of an issue since the aberrations generally increase as you move away from the lens center. Keeping mind of the focus offset, dose trade-off, we were able to successfully print 700 nm holes and lines forming the spaces between the holes that were 415 nm wide.

Using an inductively coupled plasma Versaline ICP/RIE etcher in conjunction with a CHF$_3$ chemistry, the chrome masking layer pattern can be transfer etched into the dielectric SiO grating layer. The following table summarizes the process parameters used for the dry transfer etching process.
Table 4-4: Summary of etching process parameters.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICP Power</td>
<td>1000 W</td>
</tr>
<tr>
<td>RIE Power</td>
<td>500 W</td>
</tr>
<tr>
<td>CHF₃ Gas Flow</td>
<td>50 sccm</td>
</tr>
<tr>
<td>O₂ Gas Flow</td>
<td>5 sccm</td>
</tr>
<tr>
<td>Pressure</td>
<td>10 mTorr</td>
</tr>
</tbody>
</table>

Etching the structures for a total time of 1 minute and 15 seconds, the following AFM data depicts the transfer etched GMRF structure with the chrome hard mask remaining. Taking into account the chrome mask thickness information from Figure 4-5, this results in an etch depth into the nitride layer of 273 nm. An SEM image taken at 20 kV of the top surface of the filter after the chrome masking layer is removed is provided in the figure that follows the AFM data.

Figure 4-6: AFM data of etched GMRF with chrome masking layer remaining.
The HGMRF was optically characterized using a tunable laser source with an output pigtailed to a fiber collimator. This fiber collimator provided a 2 mW, 380 µm diameter (FWHM), collimated output beam which was passed through the HGMRF and collected with another matching fiber pigtailed collimator which was fed into a detector synchronized with the tunable source. The figure below depicts the reflection characteristics of the HGMRF, providing ~ 0.15 nm line-width highly efficient reflection with a 20 dB side mode suppression ratio. The presence of the small side band originates from small deviations in hole depth from area to area of the GMRF that may arise due to overall uniformity issues within the area illuminated by the test beam.
Figure 4-8: Experimental reflection data of HGMRF.

In comparison to the predicted reflection response of the GMRF provided through RCWA modeling results, there is a drop in absolute reflection which can be attested to the effect of the finite beam size incident on the GMRF. The modeling results presented here assumes infinite plane waves normally incident to the filter. As observed in [56], after a plane wave decomposition of an incident, collimated beam has been performed, and this entire angular spectrum used as the incident field to the filter, a reduction in filter efficiency and overall performance is observed. This effect of a finite beam was seen to be a function of the overall number of periods that the beam interacts with. The drop in reflection efficiency observed here matches with what would be expected given the beam size incident on the filter during characterization.
4.2.3 SGMRF: E-beam Result

The second design for the GMRF utilizes an electron-beam lithography based exposure system to pattern a square lattice symmetry hole-array GMRF (SGMRF) multilayer dielectric structure. Unlike the case of the HGMRF, there is virtually no limitation on filter aperture size, however, the height mapping component and write time of the e-beam system itself limits the extent to which designs are feasible to pattern using this technique depending on the feature size and pattern density. The following figure provides SEM metrology, at two different magnifications, of the top surface of a sample after exposure and subsequent development demonstrating the ability to pattern hole-arrays using the e-beam lithography approach over a relatively large 2 cm x 2 cm area.

Figure 4-9: SEM images of hole-arrays patterned in ZEP-520A.
Using the parameters summarized in Table 4-1 for the SGMRF design, the SiN and SiO films were deposited using the PECVD technique onto a 4” SiO2 wafer. Because electron beam lithography is used in this approach to pattern the hole-arrays, as mentioned in section V.2, a charge release layer must be present due to the insulating properties of the dielectric stack. This layer serves two purposes, one as this charge release layer for the lithography, and two, as hard mask for the transfer etching of the hole array pattern into the grating SiO layer. A 100 nm layer of thermally evaporated chrome was therefore deposited onto the surface of the filter sample and coated with ZEP-520A at a spin speed of 5000 rpm for a resist thickness of 375 nm. As done in the spectral transmission filter work, the proximity effect was utilized in order to efficiently pattern the hole-arrays depicted above, taking advantage of the inherently circular nature of the electron beam itself used to perform the exposures. Again, a chrome charge release and etch masking layer was thermally evaporated onto the multilayer dielectric surface. For the specific beam current, step size, and resolution, the information presented in section 5.1.3 provides the dose to hole diameter characterization used to determine the dosage necessary to pattern the hole-array with individual holes of a specific diameter. In this case, the design allocates a hole diameter of 450 nm etched into the grating SiO layer. A target size of 300 nm was used for the patterning of the hole-array individual elements to take into account the increase in feature size that is consistent with the wet etching process used subsequently to transfer the resist pattern into the chrome masking layer. The following SEM image depicts the hole-array pattern in ZEP using a dose of 6900 µC/cm² and a corresponding dark field microscope image verifying dose to clear across the filter aperture.
Knowing that the sample has satisfied dose to clear criteria, a commercially available chrome etchant was used for 70 seconds followed by a DI H₂O rinse in order to transfer the hole array into the chrome masking layer in preparation for the SiO dry etching. The AFM data presented below depicts the SGMRF structure after this wet etching has been completed and ZEP removed showing 445 nm holes, etched completely through the chrome masking layer.
After a brief oxygen plasma descum cleaning process, and using the same etching chemistry as summarized in Table 4-4, this hole-array pattern was transfer etched into the SiO grating dielectric layer. An image of the AFM data obtained of the final SGMRF demonstrating the final structure with hole diameter of 450 nm and etched depth of 130 nm.
Figure 4-12: AFM data of final SGMRF component

Again, using the same testing routine used to characterize the HGMRF sample, the spectral reflective characteristics of the SGMRF were experimentally verified. Results demonstrated a 90% reflection efficiency for a reflection resonance located at 1556.95 nm and 0.15 nm linewidth. No additional side bands were detected over the wavelength range determined by the gain bandwidth of the DCOF structure. The following figure is the experimentally determined reflection characteristics of the SGMRF design filter.
Figure 4-13: Experimental data for reflection characterization of SGMRF design filter

4.3 Fiber Laser Testing and System Characterization

For the DCOFL operated in an external cavity configuration, the single resonance HGMRF structure was used as the external feedback, spectrally selective resonator mirror. This filter provides the high efficiency, narrow line-with reflection desired for this type of system with the additional benefit of being transparent to the pump wavelengths. These factors facilitate the use of a convenient optical pumping scheme for the DCOF structure as depicted below.
4.3.1 DCOFL External Cavity Setup Description

![Diagram of Coupling/Collimation Optic](image)

**Figure 4-14:** Experimental test setup using HGMRF as external feedback element in DCOFL

The two main objectives of the following experimental work were to utilize a convenient and efficient pumping scheme and to provide external, spectrally selective feedback to the DCOFL via a GMRF within the gain bandwidth supported by the doped-DCOF structure itself. The pump beam was supplied for these experiments via a multimode pump module with a pigtailed multimode fiber (MMF) output (dcore = 105 µm). This output was collimated and injected into the resonator system through the backside of the GMRF. A microscope objective lens was used to enable the multimode pumping of the doped, double cladding fiber section. The side of the objective towards the end facet of the fiber had an anti-reflection (AR) coating covering the c-band wavelengths. This enabled the same optic to also provide the collimation of the signal beam interacting with the GMRF to form the external cavity DCOFL with the cleaved facet of the DCOF on the other end of the resonator.
4.3.2 Pumping Scheme

The pump beam was collimated and injected through the backside of the HGMRF. For an input pump power of 3.481 W, power measurements showed a transmitted power of 3.35 W that was subsequently coupled into the DCOF structure. Spectral measurements verified that there were no additional resonances within the pump wavelength range as a result of the pump beam passing through the HGMRF. In order to utilize this pump source in our fiber laser experiments, it was necessary to optically and electrically characterize the pump beam in our specific system. The following figures provide the characterization data for the MM pump module including light-current-voltage (LIV) characterization as well as spectral content in the output pump beam at a drive current of 2 A obtained using a spectrum analyzer.
4.3.3 External Cavity DCOFL Test Data and Analysis

Once a maximum coupling efficiency was achieved, the critical alignment of between the HGMRF and the DCOF was performed by observing the output spectrum provided from the spectrum analyzer. Having detected the external wavelength selective feedback on the spectrum analyzer, the alignment was further optimized and pump power reduced below threshold to observe the amplified spontaneous emission spectrum from the external cavity DCOFL. This ASE spectrum from the DCOFL, operated in an external cavity configuration, was captured.
using the spectrum analyzer and is presented as follows. As mentioned in the introduction section, the gain bandwidth can be approximated from this figure to span from ~ 1500-1600 nm. The external spectrally selective element provides wavelength stabilization within this spectrum.

![ASE Spectrum from DCOFL](image)

**Figure 4-17: ASE Spectrum from DCOFL**

The pump power was subsequently increased beyond threshold to characterize the wavelength stabilized output spectrum from the DCOFL. The following figure represents the wavelength stabilized output to a wavelength of 1540.8 nm with a line-width of ~ 0.18 nm (FWHM) for a pump power of 5.43 W with 439 mW in the locked wavelength output beam.
This externally stabilized beam with spectral peak located at 1540.8 nm with a line-width of approximately 0.18 nm was observed at the output of the external cavity DCOFL where the nearest side band is 20 dB down from the peak wavelength. This again can be attested to the non-uniformity of the hole depths across the filter aperture that the signal beam is incident upon. Small variations in these hole depths have been seen, in the characterization of the HGMRF as a wavelength selective feedback element, to provide small side band resonances that match the location of the side bands seen in this DCOFL output spectrum. Using a binary diffraction grating to separate any residual pump beam at the output of the DCOFL from the signal, core beam, the light current characteristics of the DCOFL can be obtained. The following figure
presents the pump module drive current vs DCOFL output power for the 1540 nm signal beam. A near field image of the single mode output from the DCOFL is also provided in the inset of this figure obtained via a CCD camera focused at the LR output facet of the DCOF structure.

**Figure 4-19: LI characterization and SM output image of external cavity DCOFL output**

The relationship between input pump power and output power in the wavelength stabilized output can be determined taking into account the LI characteristics of the MM pump module used throughout this work and is shown below.
Figure 4-20: Input MM Pump Power vs. Output Wavelength Stabilized Power

This figure demonstrates the threshold power value of 1.965 W and slope efficiency of 0.13 beyond this pumping power level. As mentioned previously, by adopting this fiber laser configuration, the core/signal beam is expanded and collimated before it interacts with the GMRF, effectively distributing the power density over a diameter of approximately 400 µm (FWHM). Combined with the material set used, this makes this feedback mechanism more resilient to the thermal and non-linear effects that are synonymous with FBGL’s when discussing scalability for operation at higher power levels as observed in [57,58,59]. The emitted spectrum from this external cavity configuration DCOFL did not shift as a result thermal issues associated with an increase in pump power and output power levels.
5 CHAPTER V: FABRICATION METHODS APPENDIX

The fabrication processes for the different MOSSE structures presented in this work can be discussed in terms of three specific stages within the overall process flow: thin film deposition, lithography, and the transfer etching stages. Process flows have been developed for each MOSSE structure such that each stage of the fabrication process is carried out in a sequential manner, without any intermediate fabrication steps within that particular stage of the process flow. The contents of this appendix serve to provide an abridged background of the different fabrication methods adopted in this body of work beginning by address the 3 different lithographic approaches to patterning of sub-wavelength feature size hole-arrays used throughout this work. A process based overview and optical characterization of the PECVD thin films used in this work follows this lithographic discussion. The transfer etching process stage is then discussed in terms of hard and soft masking options given the etch chemistries and process parameters used in the different MOSSE structures discussed in this text.

5.1 Lithography

Out of the three specific stages within the overall process flow, the lithography stage of the fabrication process provides the most flexibility in terms of the different options available to our research group to perform the lithographic exposures. Depending on the overall pattern size and individual element feature sizes, different lithographic exposure tools may be more convenient and efficient to use in comparison to another. The three different lithographic exposure tools utilized in the fabrication process development for the MOSSE structures presented here can be categorized as contact, projection, or electron beam based. All three different types of lithography have been used to pattern sub-wavelength diameter hole-arrays into photoresist
layers, with each technique having its own unique set of challenges and limitations. The processes used to transfer etch any lithographically patterned area into an underlying substrate material is unique in each different approach, but can be generalized to a certain extent, as shown in the following table for positive photoresist processing.

Table 5-1: Generic photolithographic flowchart for pattern transfer into substrate material using positive photoresist

<table>
<thead>
<tr>
<th>GENERIC PHOTOLITHOGRAPHY PROCESSING FLOWCHART</th>
</tr>
</thead>
<tbody>
<tr>
<td>FABRICATION STEP</td>
</tr>
<tr>
<td>1. Substrate treatment</td>
</tr>
<tr>
<td>2. Surface treatment</td>
</tr>
<tr>
<td>3. Photoresist application</td>
</tr>
<tr>
<td>4. Soft bake</td>
</tr>
<tr>
<td>5. Exposure</td>
</tr>
<tr>
<td>6. Resist development</td>
</tr>
<tr>
<td>7. Visual inspection</td>
</tr>
<tr>
<td>8. Hard bake</td>
</tr>
<tr>
<td>9. Etch</td>
</tr>
<tr>
<td>10. Strip photoresist</td>
</tr>
<tr>
<td>11. Visual inspection</td>
</tr>
</tbody>
</table>

5.1.1 Quintel Mask Aligner for Contact Based Lithography

Contact based lithography is commonly used for 1:1 feature transfer of a patterned photomask to a photoresist layer due to the wide variety of commercially available exposure systems that
provide controllable exposure environments without complex user interfacing. As can be inferred from the name, contact lithography entails the photomask being in direct contact with the surface of the photoresist coated substrate wafer where the features on the photomask are transferred to the resist layer based off of the openings in the patterned photomask. The following figure provides a photograph of the Quintel 7000 Series I-Line Mask Aligner used in this work, along with a basic schematic of the contact lithography process.

![Photograph of Quintel mask aligner exposure system](image)

![Schematic of contact lithography process](image)

Figure 5-1: (a) Photograph of Quintel mask aligner exposure system (b) schematic of contact lithography process

The Quintel mask aligner has a resolution specification of the 1µm, however, actual resolution limits depend strongly on the particular exposure process being used in terms of process parameters such as substrate/resist type, thickness, vacuum level, and substrate/resist
layer uniformity. Working at the resolution limit of this mask aligner requires maintaining consistent vacuum levels during the exposure process and minimizing any non-uniformities in the air gap present between the mask and photoresist coated substrate sample. In order for exposure routine optimization to be performed, several fabrication process variables need to be fixed such that the only parameterization deals with the exposure time. In order to minimize the air gap between the photoresist layer and the photo-mask surface during the lithographic exposure process, the tool is operated in a “vacuum” and minimum separation mode where the wafer and photo-mask are forced into contact with each other and a strong, stable vacuum level is achieved. For positive photoresist based contact lithography, it is necessary to add an additional process step to the contact exposure process where compensation is made for the slight elevation in resist thickness that occurs at the edges of the wafer post resist spinning, termed edge-bead removal. This step is crucial for operating the tool in the regime of the resolution limit since in order to maintain uniform exposures criteria, the photo-mask and wafer plane must be parallel to each other in order to critically maintain a uniform, minimized air gap across the wafer surface/photo-mask interface. When substrate wafers are coated with uniform thickness photoresist layers and proper edge bead removal procedures are performed, the prior mentioned air gap can indeed be minimized allowing for printing of 750 nm feature size patterns using the Quintel mask aligner. Given this limit reached on feature size, the Quintel mask aligner becomes a viable exposure tool option given the necessity to pattern hole-array patterns into photoresist that are prevalent throughout the scope of this research. The following figure provides a microscope image of 750 nm diameter hole-arrays printed in photoresist with this tool over a 1 cm x 1 cm area. In addition, SEM images are provided for MMI splitters and Littrow
gratings fabricated using this tool, again demonstrating the ability to operate the mask aligner around and below the specified resolution limits.

Figure 5-2: (a) Microscope image of 750 nm diameter hole-array printed in photoresist (b) SEM image of input to MMI device with 980 nm line-width (c) Littrow grating with 800 nm line width printed in photoresist
5.1.2 **GCA Stepper for Projection Based Lithography**

The projection based lithographic exposure tool used in this work comes from the integrated circuit (IC) industry where exposures are made in a step and repeat fashion across a wafer surface, thus the term “stepper”. Essentially, features contained on a chrome mask are reduced and imaged on a wafer surface, where, after each exposure, the wafer is translated in order to repeat a subsequent exposure at another location on the wafer surface. A GCA stepper used in this work provides a G-line ($\lambda = 436$ nm) exposure, with a NA of 0.38, and an image reduction of 5:1.
The figure above depicts a photograph of the stepper tool as well as basic schematics providing an overview of the main exposure components contained within the stepper. This stepper exposes typical field sizes ranging from 0.5 – 3 cm² using a Koehler illumination configuration to ensure the mask plane is uniformly illuminated. As discussed in chapter V, it is possible to use this exposure system to pattern hole-arrays into photoresist to meet design
specifications for the HGMRF presented as an external feedback element using a fabrication process flow similar to that summarized in table A.1. In order for these exposures to be performed uniformly across the wafer surface, a few challenges arise that are inherent in the stepper tool itself when it is operated at its resolution limit as required from the design of the HGMRF. The HGMRF design requires lithographic printing of 800 nm holes that are only separated by 415 nm over a 1.4 cm x 1.4 cm area. With the masking apertures of the stepper opened completely, a 1.4 cm² printing area on the wafer plane is possible given the 5:1 optical reduction of feature sizes contained on the photomask. The projection optic section of the exposure column depicted in figure A.2(c) introduce aberrations into the imaging of the photomask features onto the wafer plane as you move away from the lens on-axis center. Because of this, resist uniformity on the wafer surface as well as overall wafer surface quality become more important fabrication variables to take into consideration when printing features of this size. When working at the resolution limit of the exposure tool, for uniform printing of the hole array contained on the photomask, an optimization of the dose and focus offset parameters of the exposure had to be performed. These values had to be chosen such that dose to clear of the resist and uniformity criteria were satisfied across the entire printed die. Because a thinned version of S1805 photoresist (thickness of 240 nm) is used in this work, the inevitable, even though minimized, resist variation across the surface of the wafer further complicates the optimization process. Certain combinations of these values may lead to different zones across the same die having different hole diameters where certain zones may not satisfy dose to clear criteria, compromising the subsequent transfer etching processes. The following AFM images demonstrate two zones on the same die that were exposed with non-optimized values for the dose and focus offset leading to significant differences between the two locations on the die
where the diameters of the individual hole-elements of the pattern are different and one zone does not satisfy dose to clear criteria.

![AFM images of two different zones contained within individual die with non-optimized values for dose and focus offset.](image)

**Figure 5-4:** AFM images of two different zones contained within individual die with non-optimized values for dose and focus offset.

Iterating through the different combinations of dose and focus offset parameter values and performing metrology at different locations across a die can be approached by initially determining focus offset values that lead to dose to clear validation across the die without overexposing the patterns. The following AFM images demonstrate metrology performed at two different locations contained with the same die for a focus offset value where the dose to clear criteria has been satisfied at both locations. These values for focus offset and dose are closer to the optimized values, however, the non-uniformities in feature size have not been minimized.
Figure 5-5: AFM data of two different zones contained within individual die with focus offset parameter and dose trade-off partially optimized.

Once the values for the focus offset and dose has been optimized, it is possible to print uniform dies across a 1.4 cm x 1.4 cm area. The following AFM data demonstrates this where the feature sizes across the die are of the same diameter and all satisfy dose to clear criteria.
5.1.3 **Leica EBPG 5000+ for E-beam Based Lithography**

The third option available for lithographic exposures available to us is the Leica 5000+ Electron Beam Pattern Generator System. This particular system uses a thermal field emitter electron source capable of patterning 10 nm features on substrates as large as 5” x 5” operated at 20-50 kV with a 100 kV option. The system has a maximum field size of 800 µm x 800 µm where the stitching can be minimized due to off-axis correction and height sensor capabilities in conjunction with a HeNe interferometer automated stage movement control accuracy of 0.6 nm.
The following figure provides a photograph of the Leica tool used in this work along with a generalized schematic of the electron beam column.

Figure 5-7: (a) Leica 5000+ EBPG system used in this work (b) schematic of electron beam column (Leica Vector Beam Writer)

The electrons are produced by the emitter at the top of the column where the electrostatic and magnetic lenses are responsible for condensing of the beam. The system is also equipped with an automatic stigmator module which corrects any residual astigmatism in the electron beam. ZEP-520A, a chemically amplified positive photoresist, is used in this work over the standard PMMA resist due to its increased sensitivity, thus decreasing the write time.

In order to efficiently pattern hole arrays into photoresist, we utilize the proximity effect [104] in electron beam lithography that can be described through the various scattering events
that occur when an electron strikes the substrate after traversing the resist layer during the exposure process. Fundamentally, the resulting back scattered electrons contribute to the overall dose applied to the particular feature and a broadening of the feature size is observed. Because the exposing electron beam is inherently circular in nature, by operating the EBPG system in a flash and repeat format, hole-arrays can be efficiently patterned into the photoresist layer. The figure below depicts the assigned target grid contained within the write file used as location points to perform these exposures using the Leica tool.

Figure 5-8: Target grid for e-beam lithographic exposures of hole-arrays
This exposure routine requires a characterization of the exposure dose and resulting hole diameter for the specific substrate structure and photoresist layer thickness. The following SEM images depict this effect used to pattern square lattice symmetry hole-arrays into a 375 nm thick ZEP layer using a 100nA beam as the dose is varied from 1500-1700 µC/cm² increasing the hole diameter accordingly.

Figure 5-9: Hole diameter increase as dose is increased.
Given this characterization, hole-array patterns can be patterned to match design specifications where the e-beam accurately places the periodicities of the hole-array individual elements.

5.2 PECVD of Multiple Thin Film Layers

The backbone of this research entails the deposition of multiple thin film layers upon a substrate wafer utilizing a plasma enhanced chemical vapor deposition (PECVD) process where film growth is performed using a gas phase precursor activated in a glow discharge environment. The optical characteristics of the thin films are contingent on the precursor gases and on the plasma-surface interactions that occur during the thin film deposition process.

5.2.1 STS Multiplex PECVD

The STS PECVD Multiplex tool used in this work is operated using a high frequency, 13.56 MHz, discharge frequency which effectively negates surface charging and plasma instabilities. Through control of the process chamber pressure, gas flow, power, temperature, and excitation frequency, the optical characteristics of the thin films deposited can be tailored to match application requirements. The STS PECVD Multiplex module is depicted below where the process chamber, electronics rack, and external chiller/rough pump provide the process control required for the thin films required in this work.
Thin film characterization was performed for two high frequency SiO and SiN transparent dielectric layers. The table below summarizes the process parameters used to deposit the two respective thin film layers required throughout this research work.
The fundamental first stage in the filter fabrication is the optical thin film characterization of the two chosen high/low refractive index dielectric films in terms of the wavelength dependent index of refraction and deposition rate in order to grow the multilayer dielectric stack component of the filter with the correct thicknesses and optical properties. Using an n and kappa analysis tool, the wavelength dependent optical parameters were determined over a wavelength range of 190-1000 nm. It is reasonable to assume that these films are optically transparent since the kappa values measured for both SiO and SiN films were less than $10^{-4}$ over the wavelengths of interest. This data was curve fitted to generate the required Sellmeier’s coefficients to extrapolate the index of refraction data to the longer wavelengths of interest. This is expressed functionally in the equation that follows, where the constant parameters along with the index of

---

**Table 5-2: Process parameter summary for PECVD SiO/SiN dielectric layers**

<table>
<thead>
<tr>
<th>Process</th>
<th>Parameter Description</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiN Deposition</td>
<td>Showerhead Temperature</td>
<td>250 °C</td>
</tr>
<tr>
<td></td>
<td>Platten Temperature</td>
<td>300 °C</td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
<td>900 mTorr</td>
</tr>
<tr>
<td></td>
<td>N2 Gas Flow</td>
<td>1910 sccm</td>
</tr>
<tr>
<td></td>
<td>100% SiH4 Gas Flow</td>
<td>36 sccm</td>
</tr>
<tr>
<td></td>
<td>NH3 Gas Flow</td>
<td>52 sccm</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>20 W</td>
</tr>
<tr>
<td></td>
<td>Load %</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Tune %</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Deposition Rate</td>
<td>9.897 nm/min</td>
</tr>
<tr>
<td></td>
<td>Refractive Index @ 1550 nm</td>
<td>1.936</td>
</tr>
<tr>
<td>SiO Deposition</td>
<td>Showerhead Temperature</td>
<td>250 °C</td>
</tr>
<tr>
<td></td>
<td>Platten Temperature</td>
<td>300 °C</td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
<td>900 mTorr</td>
</tr>
<tr>
<td></td>
<td>N2 Gas Flow</td>
<td>390 sccm</td>
</tr>
<tr>
<td></td>
<td>100% SiH4 Gas Flow</td>
<td>10 sccm</td>
</tr>
<tr>
<td></td>
<td>N2O Gas Flow</td>
<td>1410 sccm</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>30 W</td>
</tr>
<tr>
<td></td>
<td>Load %</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Tune %</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Deposition Rate</td>
<td>53.26 nm/min</td>
</tr>
<tr>
<td></td>
<td>Refractive Index @ 1550 nm</td>
<td>1.4496</td>
</tr>
</tbody>
</table>

---

120
refraction and deposition rate information for the SiO and SiN films are listed in the subsequent table.

\[ n(\lambda) = A + \frac{B \lambda^2}{\lambda^2 - C^2} \]  

Table 5-3: Sellemier coefficient for curve fitting and extrapolation out to longer wavelengths.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>n((\lambda = 1550) nm)</th>
<th>Deposition Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiN</td>
<td>0.86435</td>
<td>1.09665</td>
<td>120.2972</td>
<td>1.9676</td>
<td>9.81 nm/min</td>
</tr>
<tr>
<td>SiO</td>
<td>1.05215</td>
<td>0.39516</td>
<td>89.0296</td>
<td>1.4486</td>
<td>53.37 nm/min</td>
</tr>
</tbody>
</table>

The figure that follows depicts the optically characterized wavelength dependent index of refraction combining both the experimentally obtained data with the extrapolated data provided via the Sellemier’s coefficient curve fitting. This provides index of refraction characterization of both films from wavelengths of 200-1600 nm.
Figure 5-11: Wavelength dependent index of refraction of SiO (blue) and SiN (red) dielectric layers.
CHAPTER VI: CONCLUSION

Over the scope of the research presented here, different solutions have been demonstrated in order to engineering and condition the spatial, spectral, amplitude, phase, and polarization characteristics of incident IR beam using composite structures. These MOSSE structures have been shown to provide space variant optical functionality due to the sequential fabrication processes utilized towards the realization of these components. This was made possible due to the enabling technologies that have been available to us allowing for a broader range of options when it comes to the lithographic nano/micro-patterning, dielectric growth, and transfer etching capabilities. Two versions of a spatially variant, optical transmission filter were fabricated. The performance of each filter utilizing different tuning mechanisms was verified in comparison to RCWA simulations performed predicting filter transmission characteristics. Each filter was shown to provide a narrow line-width spectral transmission peak with a high level of transmission efficiency. The second MOSSE structure utilized an auto-cloning multiple thin film deposition technique to develop a SPACE structure that provided a conversion from an incident linearly polarized beam to a transmitted azimuthally polarized beam. This SPACE structure provided this optical functionality with a transmission efficiency above 90%. The final MOSSE structure used a spectrally selective feedback element in an external cavity DCOFL. This external feedback element was fabricated using two different lithographic exposure tools to realize two versions of the GMRF’s. External wavelength stabilization of a DCOFL using a 2-D GMRF was achieved providing an emitted spectrum with a line-width of tens of nanometers, with an output power up to 900 mW.
LIST OF REFERENCES:


20 R. Rumpf," Design and optimization of nano-optical elements by coupling fabrication to optical behavior,” *Dissertation*, University of Central Florida, 2006


52 L. P. Zeon Chemicals, "[www.zeonchemicals.com](http://www.zeonchemicals.com)"
53 L. Microsystems, "www.leica-microsystems.com."

54 I. Transene Company, "www.transene.com."


