Diffractive Optics: Design, Fabrication, and Applications

G. Michael Morris

The Institute of Optics
University of Rochester
Rochester, New York 14627

(716) 275-5140 TEL
(716) 271-1027 FAX

and

Rochester Photonics Corporation
330 Clay Road
Rochester, New York 14623

(716) 272-3010 TEL
(716) 272-9374 FAX
Diffractive (or Binary) Optics

Features

- Large aperture and lightweight elements
- Aspheric wavefront generation
- Achromatization of optical systems
- Reduction in weight and number of lenses
- Eliminates the need for exotic materials
- Synthesis of key research and development issues

  Extensive technological leveraging

  Replication methods for mass production
**Diffractive (or Binary) Optics**

**Applications**

**Narrowband (Laser) Optics**

- Wide-field Imaging
- Fourier Transform Lenses
- Collimation & Beam Expansion
- F-Theta Scan Lenses
- Anamorphic (Cylindrical Elements)
- Microlens arrays --Hartmann Sensors, Laser Diodes and Detector Arrays
- Optical Interconnects
- Null Optics for Interferometric Testing

**Broadband Optical Systems**

- Hybrid Diffractive/Refractive Achromats
- Beam Shaping for Diode Lasers
- Bi-Focal Contact & Intraocular Lenses
- Optical Data Storage
- Head-up (HUD) and Head-Mounted (HMD) Displays
- Aft-Imager Optics for NASA Sensors
- Integrated Optics
Diffractive (or Binary) Optics

Applications (cont'd)

Sub-Wavelength Structured Surfaces

Anti-Reflection Structured (ARS) Surfaces
  Windows and Domes
  Low Observable (Stealth) Technology
  Detectors and Solar Cells

Polarization Components
  Linear Polarizers
  Waveplates (half-wave, quarter-wave)
  Retarders
  Beam Splitters

Narrowband Filters
  Static Filters (laser end mirrors)
  Tunable Filters (laser mode tuners, optical switches)
  Security Applications (Identification - friend or foe)

Athermalization of Optical Systems
Diffractive Lenses

• Phase Function of Lens

\[ \phi(r) = 2\pi (A r^2 + G r^4 + \ldots) \]

\[ r_m - r_{m-1} \approx 2\lambda F^m \]

• Diffractive Zone Boundaries

\( r_m \) is the radius such that \( \phi(r_m) = 2\pi m \)

• Blaze Height

\[ h_{\text{max}} = \frac{\lambda_0}{n(\lambda_0) - 1} \]

• Diffraction Efficiency (scalar diffraction theory)

<table>
<thead>
<tr>
<th>Blaze</th>
<th>Peak Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polynomial</td>
<td>100 %</td>
</tr>
<tr>
<td>Linear</td>
<td>99 %</td>
</tr>
<tr>
<td>16 level</td>
<td>98.7 %</td>
</tr>
<tr>
<td>8 level</td>
<td>95 %</td>
</tr>
<tr>
<td>4 level</td>
<td>81.1 %</td>
</tr>
</tbody>
</table>
Surface Relief Diffractive Optics

Advanced Designs Exist!

Fabrication of Surface Master

Photolithography
Multiple e-beam masks
(staircase blaze profile)

Diamond Turning
Linear and spherical blaze

Laser Writer System
Vary exposure to shape blaze profile

Replication Methods

Compression Molding

Cast and Cure Methods
(excellent temperature & mechanical properties)
Binary Optics Lens
4-Level

Etched Silicon Master

Electro-Formed Nickel Master
Blazed Diffractive Lens

F.L. = 75 mm, f/#3, $\lambda_0 = 587.6$ nm
Laser Pattern Generator
(Single-Point, X-Y)

Specifications

- **Wavelength**: 441.6 nm
- **Spot Size**: 0.7 - 10 μm
- **Pixel Spacing**: 0.25 - 5 μm
- **Edge Location Error**: < 0.7 μm per 0.03 μm/inch
- **Part Size**: 4" x 4" x 0.5"
- **Write Time**: 3.1 hrs/100 sq. mm
- **Phase Levels**: 2 - 256
- **Substrate Curvature**: < 3λ/inch
- **Photoresist Thickness**: 0.2 - 3 μm
Diffractive Landscape Lens

Modulation Transfer Functions

F/5.6  F = 50 mm  λ₀ = 587.6 nm

Holographic  Diffractive Landscape

HFOV = 4.5 deg
Achromatic Doublet

- Lens Powers

\[ \phi_a = \frac{V_a}{V_a - V_b} \Phi \]

- Abbe numbers

\[ 20 < V_{\text{glass}} < 90 \]
\[ V_{\text{DOE}} = -3.45 \]

- Conventional Doublets

\( V_a = 60 \) crown
\( \phi_a = 2.5\Phi \)
\( V_b = 36 \) flint
\( \phi_b = -1.5\Phi \)

- Hybrid Doublet

\( V_a = 60 \) crown
\( \phi_a = 0.95\Phi \)
\( V_b = -3.45 \) DOE
\( \phi_b = 0.05\Phi \)

- Features of Hybrid Doublets

lower curvatures
lower F/#
lower weight
no need for exotic glasses
Application - Optical Data Storage

- General ODS element

  - Positive singlet
  - Disk coating
  - F/0.9
  - f ≈ 3.0mm
  - HFOV = 1°
  - λ₀ = 0.780 ± 0.01μm
  - Monochromatic

- Conventional Glass Doublet

  - Crown
  - Flint
  - Conventional achromatic doublet adds weight and size

- Hybrid Doublet

  - Hybrid lens reduces weight, and helps correct other aberrations
Strehl Ratio vs Field Angle

- Numerical Apertures:
  - Hybrid Doublet - 0.57
  - Olympus Triplet - 0.50
  - SF57 Singlet - 0.53
Waveguide Lenses

Mode-Index Diffractive Achromatic Hybrid

Longitudinal Chromatic Aberration

![Graph showing the comparison of focal length error for different types of lenses against wavelength error. The graph includes curves for Fresnel Lens, Hybrid Lens, and Mode-Index Lens.]
Waveguide Lens Comparison

\[ t_B = 0.67 \mu m \quad t_L = 0.37 \mu m \]

Corning 7059

Pyrex

\[ N_B = 1.532, \quad N_L = 1.497 \]
\[ \Delta N = -0.035 \]

focal length = 10mm, F/5

Mode-Index Lens

Diffractive Lens

\[ h_0 = 17.5 \mu m \]
\# zones = 54

smallest zone = 6.1 \mu m

Hybrid Achromatic Lens

Mode-index surface

\[ f_{\text{ni}} = 5.3 \text{mm} \]

Diffractive surface

\[ f_d = -11.5 \text{mm} \]
\[ h_0 = 17.5 \mu m \]
\# zones = 47

smallest zone = 7.0 \mu m
Waveguide Lens Performance Comparison

<table>
<thead>
<tr>
<th></th>
<th>Insertion Loss</th>
<th>Diffraction Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode-Index Lens</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>Diffractive Lens</td>
<td>40%</td>
<td>70%</td>
</tr>
<tr>
<td>Hybrid Achromatic Lens</td>
<td>40%</td>
<td>70%</td>
</tr>
</tbody>
</table>

Wavelength Range for Strehl Ratio > 0.8

(Depth of focus = 44 µm)

Mode-Index: 11 nm
Diffractive: 5 nm
Hybrid: 49 nm
Diffractive Lens Imaging

- Undiffracted light forms background in image plane

Diffractive Lens

Image Plane

- Optical Axis

\[ m = 1 \]

\[ m = 2 \]

\[ m = 0 \]

\[ f/2 \]

\[ f \]

- Point Spread Function

Intensity

Other Diffracted Orders

Primary Diffraction Order

Position
Diffraction Efficiency

- Analytic result for diffraction efficiency

\[ \eta = \frac{\sin^2[\pi(\alpha - m)]}{[\pi(\alpha - m)]^2} \]

- Wavelength detuning parameter

\[ \alpha(\lambda) = \frac{\lambda_0}{\lambda} \frac{n(\lambda) - 1}{n(\lambda_0) - 1} \]
Polychromatic Examples

- $\lambda_0 = 0.55 \, \mu m$  $\lambda_{\text{min}} = 0.4 \, \mu m$  $\lambda_{\text{max}} = 0.7 \, \mu m$
- $P = 8$  F/5.6  $\eta_{\text{int,poly}} = (0.95)(0.914) = 0.868$

\begin{align*}
\text{Modulation} & \quad 1.0 \\
\text{Spatial Frequency (lines/mm)} & \quad 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \\
\text{Diffraction Limit} & \\
8 \text{ Phase Levels} & \\
0.4 \, \mu m - 0.7 \, \mu m &
\end{align*}

- $\lambda_0 = 10.0 \, \mu m$  $\lambda_{\text{min}} = 8.0 \, \mu m$  $\lambda_{\text{max}} = 12.0 \, \mu m$
- Continuous profile  F/2  $\eta_{\text{int,poly}} = 0.955$

\begin{align*}
\text{Modulation} & \quad 1.0 \\
\text{Spatial Frequency (lines/mm)} & \quad 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \\
\text{Diffraction Limit} & \\
8 \, \mu m - 12 \, \mu m &
\end{align*}
Synthesis of Phase Gratings From Known Fourier Modulus Data

Set \( b(x,y) = 1 \)

Phase Object

\( b(x,y)\exp[i\phi(x,y)] \)

\( T(f_x,f_y)\exp[i\theta(f_x,f_y)] \)

Fourier Transform

\( A(f_x,f_y)\exp[i\theta(f_x,f_y)] \)

\[ A(f_x,f_y) = \text{Desired Fourier Modulus} \]
Phase Grating Synthesis
11 x 11 Array, Equal Intensity Diffracted Orders

Desired Fourier Modulus

Phase Grating

Reconstructed Fourier Modulus
Phase Grating Synthesis
Triangular Array, Equal Intensity Diffracted Orders

Desired Fourier Modulus

Phase Grating

Reconstructed Fourier Modulus
Sub-Wavelength Structured Surfaces

Concept
Use surface structure (small compared to the illumination wavelength) to synthesize an effective index of refraction

Approach
Effective Medium Theory
Rigorous Electromagnetic Theory
Tapered Transmission-Line Theory
Fabricate using Photolithographic Techniques

Features
Supression of Fresnel Reflections
Large Field-of-View and Spectral Bandwidth
Advantages over Thin Film Coatings
   No Cohesion Problems
Birefringent Surface
ARS Surfaces

- Require **ONLY** $R_0$ and $T_0$ non-evanescent

\[
\frac{\lambda}{\Lambda} < \frac{1}{\lambda} \frac{1}{\text{Max}[n_i,n_s]} + n_i \sin \theta_{\text{max}}
\]

- Period $\Lambda$ smaller than wavelength $\lambda$

**Effective Medium Theory (EMT)**

Structured Surface

[Diagram of a structured surface with layers $n_i$, $n_s$, and $d$]

Effective Medium $n_i$

[Diagram of a film stack with layers $n_1$, $n_2$, $n_3$, and $n_s$]

Multi-level Profile

- Light averages optical properties of structured region
Angle of Incidence Sensitivity of GaAs 2-D Multilevel ARS Surfaces

- Performance for randomly-polarized radiation

![Graph showing power transmitted vs. angle of incidence for different levels of ARS surfaces.]

\[ \lambda = \lambda_0 = 10.6 \, \mu m \]

- ARS Surface Parameters

<table>
<thead>
<tr>
<th>Profile</th>
<th>Profile depth ((\mu m))</th>
<th>Duty Cycle (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary</td>
<td>1.463</td>
<td>69.7</td>
</tr>
<tr>
<td>4-level</td>
<td>3.244</td>
<td>91.7</td>
</tr>
<tr>
<td>8-level</td>
<td>4.441</td>
<td>98.5</td>
</tr>
</tbody>
</table>
Spectral Sensitivity of GaAs 2-D Multi-level ARS Surfaces

- 4-level Pyramidal Profile

- 8-level Pyramidal Profile
Experimental Work
2-D Binary ARS Surface for GaAs

- Preliminary Results: CAIBE etched GaAs

4.22k Magnification

10.00k Magnification

16.50k Magnification

Surfaces Fabricated at Cornell's National Nanofabrication Facilities (NNF)
Polarization Components using Form Birefringence

- High-Frequency Surface-Relief Gratings

Birefringence = $\Delta n = n_{E \perp K} - n_{E \parallel K}$

$\Delta n$ is a function of filling factor $f$

$$f = \frac{a}{\Lambda}$$

Maximum Birefringence
Resonance Structures

- Only Zeroth Orders Propagating \((\Lambda < \lambda)\)
- Coupling occurs between incident wave and leaky wave
- Extremely narrow FWHM possible.
- Example: FWHM of ~2Å

![Graph showing the wavelength and power reflected.](image-url)
Future Directions in Diffractive Optics

Diffractive Optics

Commercial Products
- Laser Diode Optics
- Laser Printing
- Ophthalmic Lenses
- Optical Data Storage
- Illumination Systems
- Optical Testing
- Medical Optics

Government Systems
- IR Systems
- HMDs and HUDs
- SWS Surfaces
- Micro-Optics
- Aamacronics
- Optical Interconnects
- Aft-Imagers