Diffractive Optics: Design, Fabrication, and Applications

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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 (Indentification - friend or foe)

Athermalization of Optical Systems
Diffractive Lenses

- Phase Function of Lens

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

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

- Diffractive Zone Boundaries

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

- Blaze Height

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

- 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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength</strong></td>
<td>441.6 nm</td>
</tr>
<tr>
<td><strong>Spot Size</strong></td>
<td>0.7 - 10 μm</td>
</tr>
<tr>
<td><strong>Pixel Spacing</strong></td>
<td>0.25 - 5 μm</td>
</tr>
<tr>
<td><strong>Edge Location Error</strong></td>
<td>&lt; 0.7 μm</td>
</tr>
<tr>
<td></td>
<td>per 0.03 μm/inch</td>
</tr>
<tr>
<td><strong>Part Size</strong></td>
<td>4&quot; x 4&quot; x 0.5&quot;</td>
</tr>
<tr>
<td><strong>Write Time</strong></td>
<td>3.1 hrs/100 sq. mm</td>
</tr>
<tr>
<td><strong>Phase Levels</strong></td>
<td>2 - 256</td>
</tr>
<tr>
<td><strong>Substrate Curvature</strong></td>
<td>&lt; 3λ/inch</td>
</tr>
<tr>
<td><strong>Photoresist Thickness</strong></td>
<td>0.2 - 3 μm</td>
</tr>
</tbody>
</table>
Diffractive Landscape Lens

Modulation Transfer Functions

F/5.6  F = 50 mm  λ₀ = 587.6 nm

Holographic  Diffractive Landscape
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

\[ \begin{align*}
V_a &= 60 \\
\phi_a &= 2.5\Phi \\
V_b &= 36 \\
\phi_b &= -1.5\Phi
\end{align*} \]

- Hybrid doublet

\[ \begin{align*}
V_a &= 60 \\
\phi_a &= 0.95\Phi \\
V_b &= -3.45 \\
\phi_b &= 0.05\Phi
\end{align*} \]

- 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
  
  \( f \approx 3.0\text{mm} \)
  
  \( \text{HFOV} = 1^\circ \)
  
  \( \lambda_0 = 0.780 \pm 0.01\mu\text{m} \)

- Conventional Glass Doublet
  
  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 focal length error vs. wavelength error for different types of lenses (Mode-Index, Fresnel, Hybrid) with varying wavelength errors.](image)
Waveguide Lens Comparison

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

Corning 7059

Pyrex

[N_B = 1.532, 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

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

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 Image Plane
- Optical Axis
- f/2
- f

- Point Spread Function
- Primary Diffraction Order
- Other Diffracted Orders

Intensity vs. Position
Diffraction Efficiency

- Analytic result for diffraction efficiency

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

- Wavelength detuning parameter

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

- $\lambda_0 = 0.55 \, \mu m$  \hspace{1cm} $\lambda_{\text{min}} = 0.4 \, \mu m$  \hspace{1cm} $\lambda_{\text{max}} = 0.7 \, \mu m$
- $P = 8$  \hspace{1cm} F/5.6  \hspace{1cm} $\eta_{\text{int,poly}} = (0.95)(0.914) = 0.868$

- $\lambda_0 = 10.0 \, \mu m$  \hspace{1cm} $\lambda_{\text{min}} = 8.0 \, \mu m$  \hspace{1cm} $\lambda_{\text{max}} = 12.0 \, \mu m$
- Continuous profile F/2  \hspace{1cm} $\eta_{\text{int,poly}} = 0.955$
Synthesis of Phase Gratings From Known Fourier Modulus Data

\[ A(f_x, f_y) = \text{Desired Fourier Modulus} \]
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

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

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

**Effective Medium Theory (EMT)**

Structured Surface

Effective Medium $n_i$

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 transmission vs angle of incidence for different ARS surfaces.](image)

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

- 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 $f$
  $f = a/\Lambda$

- 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 with parameters and power reflected vs wavelength](image)
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
- Amacronics
- Optical Interconnects
- Aft-Imagers