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 (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, $\lambda_0 = 587.6 \text{ nm}$
Laser Pattern Generator  
(Single-Point, X-Y)

**Specifications**

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

Modulation Transfer Functions

F/5.6  \( F = 50 \text{ mm} \)  \( \lambda_0 = 587.6 \text{ nm} \)

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

![Diagram of positive singlet lens with specifications:](image)

- Conventional Glass Doublet

![Diagram of conventional achromatic doublet with specifications:](image)

- Hybrid Doublet

![Diagram of hybrid lens with specifications:](image)
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: Fresnel Lens, Hybrid Lens, Mode-Index Lens. The graph illustrates how each lens type responds to changes in wavelength, with Fresnel Lens showing a strong positive error, Hybrid Lens showing a mild positive error, and Mode-Index Lens showing a mild negative error.](image)
Waveguide Lens Comparison

$N_B = 1.532, N_L = 1.497$
$\Delta N = -0.035$
focal length = 10mm, F/5

t_B = 0.67\mu m \quad t_L = 0.37\mu m$

Mode-Index Lens

$h_0 = 17.5\mu m$
# zones = 54
smallest zone = 6.1\mu m

Diffractive Lens

$f_{ni} = 5.3 mm$

Diffractive surface

$f_d = -11.5 mm$

$h_0 = 17.5\mu m$
# zones = 47
smallest zone = 7.0\mu m

Hybrid Achromatic Lens

Mode-index surface

Mode-Index Lens

Diffractive Lens

Hybrid Achromatic Lens
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

m = 1

m = 2

m = 0

f / 2

f

- Point Spread Function

Intensity vs. Position

Primary Diffraction Order

Other Diffracted Orders
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

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

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

Set $b(x,y) = 1$

Phase Object

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

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

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

$IFFT$

$FFT$

$A(f_x,f_y) = Desired\ Fourier\ Modulus$
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

![Diagram of Sub-Wavelength Structured Surfaces]

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

**Features**
- Suppression 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 incident wave

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

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

**Effective Medium Theory (EMT)**

Structured Surface

Multi-level Profile

Film Stack

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

- Performance for randomly-polarized radiation

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

<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>

\[ n_i = 1, n_s = 3.27, \Lambda_x = \Lambda_y = 2.480 \mu m \]
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

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

\[ \Delta n_{\text{max}} \]

\[ \begin{array}{cccc}
    n_s/n_i & 1 & 2 & 3 & 4 \\
    \Delta n_{\text{max}} & -1.75 & -1.5 & -1.25 & -1 \\
    & -0.75 & -0.5 & -0.25 & 0 \\
\end{array} \]
- Only Zeroth Orders Propagating \((\Lambda < \lambda)\)
- Coupling occurs between incident wave and leaky wave
- Extremely narrow FWHM possible.
- Example: FWHM of \(~2\text{Å}\)
Future Directions in Diffractive Optics

Diffractive Optics

Commercial Products
- Laser Diode Optics
- Laser Printing
- Opthalmic 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