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

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

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

• 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

<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 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
  \[ V_a = 60 \]
  \[ \phi_a = 2.5 \Phi \]
  \[ V_b = 36 \]
  \[ \phi_b = -1.5 \Phi \]

- Hybrid doublet
  \[ V_a = 60 \]
  \[ \phi_a = 0.95 \Phi \]
  \[ V_b = -3.45 \]
  \[ \phi_b = 0.05 \Phi \]

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

- General ODS element

  \[
  \text{positive singlet}
  \]

  \[
  \text{disk coating}
  \]

  \[
  F / 0.9 \\
  f \approx 3.0 \text{mm} \\
  \text{HFOV} = 1^\circ \\
  \lambda_0 = 0.780 \pm 0.01 \mu\text{m} \\
  \text{monochromatic}
  \]

- Conventional Glass Doublet

  \[
  \text{crown}
  \]

  \[
  \text{flint}
  \]

  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

Focal Length Error (mm)

Wavelength Error, $\Delta \lambda$ (nm)
Waveguide Lens Comparison

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

$f_{mi} = 5.3\text{mm}$

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>Lens Type</th>
<th>Insertion Loss</th>
<th>Diffraction Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode-Index Lens</td>
<td>40%</td>
<td>70%</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

\[ m = 0 \]
\[ m = 1 \]
\[ m = 2 \]

Diffractive Lens

Image Plane

Optical Axis

f / 2
f

- Point Spread Function

Primary Diffraction Order

Other Diffracted Orders

Intensity

Position
Diffraction Efficiency

- Analytic result for diffraction efficiency

\[
\eta \equiv \frac{\sin^2[\pi(\alpha - m)\sqrt{n(x)}]}{[\pi(\alpha - m)]^2}
\]

- 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 $\eta_{\text{int,poly}} = (0.95)(0.914) = 0.868$

Spatial Frequency (lines/mm)

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

Set $b(x,y) = 1$

Phase Object

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

FFT

$T(f_x,f_y)e^{i\theta(f_x,f_y)}$

Fourier Transform

$IFFT$

$A(f_x,f_y)e^{i\theta(f_x,f_y)}$

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

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

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

**Effective Medium Theory (EMT)**

Structured Surface

Effective Medium

\[
\begin{array}{c}
\text{n}_1 \\
\text{n}_2 \\
\text{n}_3 \\
\text{n}_s
\end{array}
\]

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

![Graph showing power transmitted versus angle of incidence for different profiles.]

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

- 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

\[ \Delta n = n_{E \perp K} - n_{E \parallel K} \]

- \( \Delta n \) is a function of filling factor \( f \)
  \[ f = a/\Lambda \]

- Maximum Birefringence

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

\[ 1 \quad 2 \quad 3 \quad 4 \]

\[ n_s/n_i \]
Resonance Structures

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