Diffractive Optics: Design, Fabrication, and Applications

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Conf. on Binary Optics, 1993
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

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

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

• 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>
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</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  \( F = 50 \text{ mm} \)  \( \lambda_0 = 587.6 \text{ nm} \)

Holographic  Diffractive Landscape

On-Axis

Diffraction Limit

HFOV = 4.5 deg

Diffraction Limit

T  S
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**

\[ V_a = 60 \quad V_b = 36 \]

\[ \phi_a = 2.5 \Phi \]

\[ \phi_b = -1.5 \Phi \]

- **Hybrid doublet**

\[ V_a = 60 \quad V_b = -3.45 \]

\[ \phi_a = 0.95 \Phi \]

\[ \phi_b = 0.05 \Phi \]

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

- Conventional Glass Doublet

  crown
  
  flint
  
  Conventional achromatic doublet adds weight and size

- Hybrid Doublet

  Hybrid lens reduces weight, and helps correct other aberrations
• 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 Fresnel, Hybrid, and Mode-Index lenses.](image-url)
Waveguide Lens Comparison

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

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

Intensity

Position
Diffraction Efficiency

• Analytic result for diffraction efficiency

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

• Wavelength detuning parameter

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

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

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

Set $b(x,y) = 1$

Phase Object

$\text{FFT}$

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

Fourier Transform

$B(f_x,f_y)\exp[i\phi(f_x,f_y)]$

$\text{IFFT}$

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

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

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

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

Effective Medium Theory (EMT)

Structured Surface

Effective Medium

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 with λ=λ₀=10.6 μm.]

- ARS Surface Parameters

<table>
<thead>
<tr>
<th>Profile</th>
<th>Profile depth (μm)</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 \( f \)
  \[ f = \frac{a}{\Lambda} \]

• Maximum Birefringence

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

\[ n_s/n_i \]

1 2 3 4
• Only Zeroth Orders Propagating \((\Lambda < \lambda)\)

• Coupling occurs between incident wave and leaky wave

• Extremely narrow FWHM possible.

• Example: FWHM of ~2Å

Parameters:
\[
\begin{align*}
n_0 &= 1.0, \\
n_1 &= n_3 = 1.5 \\
n_2 &= 2.0 \\
\Lambda &= 0.40\mu m \\
d_1 &= 0.30\mu m \\
d_2 &= 0.15\mu m \\
D.C. &= 50%
\end{align*}
\]
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