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

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

• 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
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

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

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

crown

• Hybrid doublet

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

crown

• Features of Hybrid Doublets

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

- General ODS element
  - F/0.9
  - f ≈ 3.0mm
  - HFOV = 1°
  - $\lambda_0 = 0.780 \pm 0.01 \mu m$
  - monochromatic

- 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

Achronatic Hybrid

Longitudinal Chromatic Aberration

![Graph showing focal length error vs. wavelength error for different lens types: Fresnel Lens, Hybrid Lens, Mode-Index Lens. The graph plots focal length error in millimeters against wavelength error in nanometers.]
Waveguide Lens Comparison

$N_B = 1.532, N_L = 1.497$
$\Delta N = -0.035$

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></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 Plane

- Point Spread Function

Intensity

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

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

![Graph showing diffraction efficiency as a function of wavelength for different values of m]
Polychromatic Examples

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

![Graph showing modulation vs. spatial frequency for polychromatic examples.](image)

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

![Graph showing modulation vs. spatial frequency for another polychromatic example.](image)
Synthesis of Phase Gratings From Known Fourier Modulus Data

\[ A(\nu_x,\nu_y) = \text{Desired Fourier Modulus} \]
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 \textit{ONLY} $R_0$ and $T_0$ non-evanescent

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

• 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 the power transmitted versus 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>

\( n_i = 1, \, n_s = 3.27, \, \Lambda_x = \Lambda_y = 2.480 \, \mu m \)
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

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

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

• Birefringence 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 \(~2\text{Å}\)

Parameters:
- \(n_0 = 1.0\), \(n_1 = n_3 = 1.5\), \(n_2 = 2.0\)
- \(\Lambda = 0.40\mu m\)
- \(d_1 = 0.30\mu m\)
- \(d_2 = 0.15\mu m\)
- D.C. = 50%
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