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**

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

- **Diffractive Zone Boundaries**

  \( r_m - r_{m-1} \leq 2\lambda F_x \)

  \( r_m \) 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

- **Wavelength**: 441.6 nm
- **Spot Size**: 0.7 - 10 μm
- **Pixel Spacing**: 0.25 - 5 μm
- **Edge Location Error**: < 0.7 μm per 0.03 μm/inch
- **Part Size**: 4" x 4" x 0.5"
- **Write Time**: 3.1 hrs/100 sq. mm
- **Phase Levels**: 2 - 256
- **Substrate Curvature**: < 3λ/inch
- **Photoresist Thickness**: 0.2 - 3 μm
Diffractive Landscape Lens

Optical Axis

Aperture Stop

Paraxial Diffractive Lens

Image Plane

Modulation Transfer Functions

F/5.6  F = 50 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

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

• 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
  
  ![Positive singlet diagram]

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

- Conventional Glass Doublet
  
  ![Conventional achromatic doublet diagram]

  \[ \text{Conventional achromatic doublet adds weight and size} \]

- Hybrid Doublet
  
  ![Hybrid diagram]

  \[ \text{Hybrid lens reduces weight, and helps correct other aberrations} \]
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.](image-url)
Waveguide Lens Comparison

- $t_B = 0.67\mu m$, $t_L = 0.37\mu m$
- $N_B = 1.532$, $N_L = 1.497$
- $\Delta N = -0.035$
- Focal length = 10mm, F/5

Mode-Index Lens

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

Diffractive Lens

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

Hybrid Achromatic Lens

- Mode-index surface: $f_{\text{mi}} = 5.3\text{mm}$
- 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 Image Plane

- Optical Axis

- Point Spread Function

- Primary Diffraction Order

- Other Diffracted Orders

Position

Intensity

47
Diffraction Efficiency

- Analytic result for diffraction efficiency

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

- Wavelength detuning parameter

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

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

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

Spatial Frequency (lines/mm)

Diffraction Limit

8 Phase Levels

0.4 \( \mu m \) - 0.7 \( \mu m \)

Continuous profile F/2 \( \eta_{\text{int, poly}} = 0.955 \)

Spatial Frequency (lines/mm)
Synthesis of Phase Gratings From Known Fourier Modulus Data

Set $b(x,y) = 1$

Phase Object

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

Fourier Transform

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

IFFT

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

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

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

**Effective Medium Theory (EMT)**

Structured Surface

Effective Medium

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

- Performance for randomly-polarized radiation

- 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>

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

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

\( \Delta n \) is a function of filling factor \( f \)

\[ f = \frac{a}{\Lambda} \]

- 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

**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
- Ophthamic 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