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

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

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

• 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>
</tbody>
</table>
| 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

Modulation Transfer Functions

F/5.6  F = 50 mm  λ₀ = 587.6 nm

Holographic  Diffractive Landscape

On-Axis

Spatial Frequency (lines/mm) 0 300

Diffraction Limit

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

\( V_a = 60 \)

\( V_b = 36 \)

\( \phi_a = 2.5\Phi \)

\( \phi_b = -1.5\Phi \)

• Hybrid doublet

\( V_a = 60 \)

\( V_b = -3.45 \)

\( \phi_a = 0.95\Phi \)

\( \phi_b = 0.05\Phi \)

• Features of Hybrid Doublets

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

- General ODS element
  
  \[
  \text{positive singlet}
  \]
  
  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
  
  \[
  \text{crown}
  \]
  
  \[
  \text{flint}
  \]

  Conventional achromatic doublet adds weight and size

- Hybrid Doublet
  
  \[
  \text{Hybrid}
  \]

  Hybrid lens reduces weight, and helps correct other aberrations
**Strehl Ratio vs Field Angle**

![Graph showing 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)
Waveguide Lens Comparison

- Corning 7059
- Pyrex

- $t_B = 0.67 \mu m$, $t_L = 0.37 \mu m$
- $N_B = 1.532$, $N_L = 1.497$
- $\Delta N = -0.035$
- Focal length = 10 mm, 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
  - $f_{\text{mi}} = 5.3 mm$
- Diffractive surface
  - $f_d = -11.5 mm$
  - $h_0 = 17.5 \mu m$
  - # 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
- Point Spread Function

```
Intensity

Position
```

Optical Axis

\[ f/2 \rightarrow f \]

Diffractive Image Plane

Diffractive Lens

\[ m = 0 \]

\[ m = 1 \]

\[ m = 2 \]
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

- $\lambda_0 = 0.55 \, \mu m$  \hspace{1cm} $\lambda_{\text{min}} = 0.4 \, \mu m$  \hspace{1cm} $\lambda_{\text{max}} = 0.7 \, \mu m$
- $P = 8$  \hspace{1cm} $F/5.6$  \hspace{1cm} $\eta_{\text{int, poly}} = (0.95)(0.914) = 0.868$

- $\lambda_0 = 10.0 \, \mu m$  \hspace{1cm} $\lambda_{\text{min}} = 8.0 \, \mu m$  \hspace{1cm} $\lambda_{\text{max}} = 12.0 \, \mu m$
- Continuous profile  \hspace{1cm} $F/2$  \hspace{1cm} $\eta_{\text{int, poly}} = 0.955$
Synthesis of Phase Gratings From Known Fourier Modulus Data

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

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

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

Effective Medium Theory (EMT)

Structured Surface \hspace{5cm} Effective Medium

Multi-level Profile \hspace{5cm} 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 vs angle of incidence for different ARS surfaces with parameters labeled.](image)

- 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

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

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

- Maximum Birefringence

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

\[ \begin{array}{c|c|c|c|c|c|c}
\hline
n_s/n_i & 1 & 2 & 3 & 4 \\
\hline
\Delta n_{\text{max}} & -1.75 & -1.5 & -1.25 & -1 & -0.75 & -0.5 & -0.25 & 0 \\
\hline
\end{array} \]
Resonance Structures

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

![Graph showing normal incidence (E||K Polarization) and parameters]

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
- 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