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 (Identification - friend or foe)

Athermalization of Optical Systems
Diffractive Lenses

• Phase Function of Lens

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

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

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

• Diffractive Zone Boundaries

\( r_m \) is the radius such that \( \phi(r_m) = 2\pi m \)

• Blaze Height

<table>
<thead>
<tr>
<th>Blaze</th>
<th>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, \( \lambda_0 = 587.6 \text{ nm} \)
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

Modulation Transfer Functions

F/5.6  F = 50 mm  λ₀ = 587.6 nm

Holographic  Diffractive Landscape

On-Axis

Spatial Frequency (lines/mm) 300

Diffraction Limit

Diffraction Limit

HFOV = 4.5 deg

Diffraction Limit

Spatial Frequency (lines/mm) 300

Modulation

Modulation

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

$$V_a = 60$$

$$V_b = 36$$

$$\phi_a = 2.5\Phi$$

$$\phi_b = -1.5\Phi$$

- 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

\[
\text{positive singlet} \\
\text{disk coating}
\]

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

• 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, Δλ (nm)
Waveguide Lens Comparison

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

Corning 7059  Pyrex

\[ N_B = 1.532, \quad N_L = 1.497 \]
\[ \Delta N = -0.035 \]

focal length = 10mm, F/5

Mode-Index Lens

\[ h_0 = 17.5\,\mu m \]
\[ \# \text{ zones} = 54 \]
\[ \text{smallest zone} = 6.1\,\mu m \]

Diffractive Lens

Hybrid Achromatic Lens

Mode-index surface
\[ f_{mi} = 5.3\,\text{mm} \]

Diffractive surface
\[ f_d = -11.5\,\text{mm} \]
\[ h_0 = 17.5\,\mu m \]
\[ \# \text{ zones} = 47 \]
\[ \text{smallest zone} = 7.0\,\mu m \]
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

Image Plane

Optical Axis

\[ m = 0 \]

\[ m = 1 \]

\[ m = 2 \]

- 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
  \[
  \alpha(\lambda) = \frac{\lambda_0}{\lambda} \frac{n(\lambda) - 1}{n(\lambda_0) - 1}
  \]
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 \( b(x,y) = 1 \)

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

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

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

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

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

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

• 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 power transmitted vs. 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>
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

\[
\begin{align*}
\Delta n_{\text{max}} & = 0 \\
& \quad -0.25 \\
& \quad -0.5 \\
& \quad -0.75 \\
& \quad -1 \\
& \quad -1.25 \\
& \quad -1.5 \\
& \quad -1.75 \\
\end{align*}
\]

\[
\begin{align*}
\text{n}_s/\text{n}_i & = 1 \\
& \quad 2 \\
& \quad 3 \\
& \quad 4 \\
\end{align*}
\]
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 and Diagram]

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