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

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

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

• Diffractive Zone Boundaries

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

• Blaze Height

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

• 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>
<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  \( \lambda_0 = 587.6 \) nm

Holographic  Diffractive Landscape

On-Axis

Diffraction Limit

HFOV = 4.5 deg

Diffraction Limit
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

F / 0.9
f ≈ 3.0mm
HFOV = 1°
λ₀ = 0.780 ± 0.01μm
monochromatic

disk coating

• Conventional Glass Doublet

Conventional achromatic doublet
adds weight and size

crown

flint

• 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 different types of lenses: Fresnel Lens, Hybrid Lens, Mode-Index Lens.]
Waveguide Lens Comparison

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

focal length = 10mm, F/5

t_b = 0.67\mu m \quad t_L = 0.37\mu m

Corning 7059
Pyrex

Mode-Index Lens

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

Diffractive Lens

Hybrid Achromatic Lens

Mode-index surface
$f_{ni} = 5.3mm$

Diffractive surface
$f_d = -11.5mm$

$h_0 = 17.5\mu m$
# 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

Image Plane

- Optical Axis

\[ m = 0 \]
\[ m = 1 \]
\[ m = 2 \]

\[ f/2 \]
\[ f \]

- Point Spread Function

- Primary Diffraction Order

- Other Diffracted Orders

Intensity

Position
**Diffraction Efficiency**

- Analytic result for diffraction efficiency

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

- Wavelength detuning parameter

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

Phase Object

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

Fourier Transform

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

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

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

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

Effective Medium Theory (EMT)

Structured Surface

Effective Medium $n_i$

Multi-level Profile

- Light averages optical properties of structured region

54
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

- 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
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:**
- \(n_0 = 1.0\)
- \(n_1 = n_3 = 1.5\)
- \(n_2 = 2.0\)
- \(\Lambda = 0.40\mu\text{m}\)
- \(d_1 = 0.30\mu\text{m}\)
- \(d_2 = 0.15\mu\text{m}\)
- 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