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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)

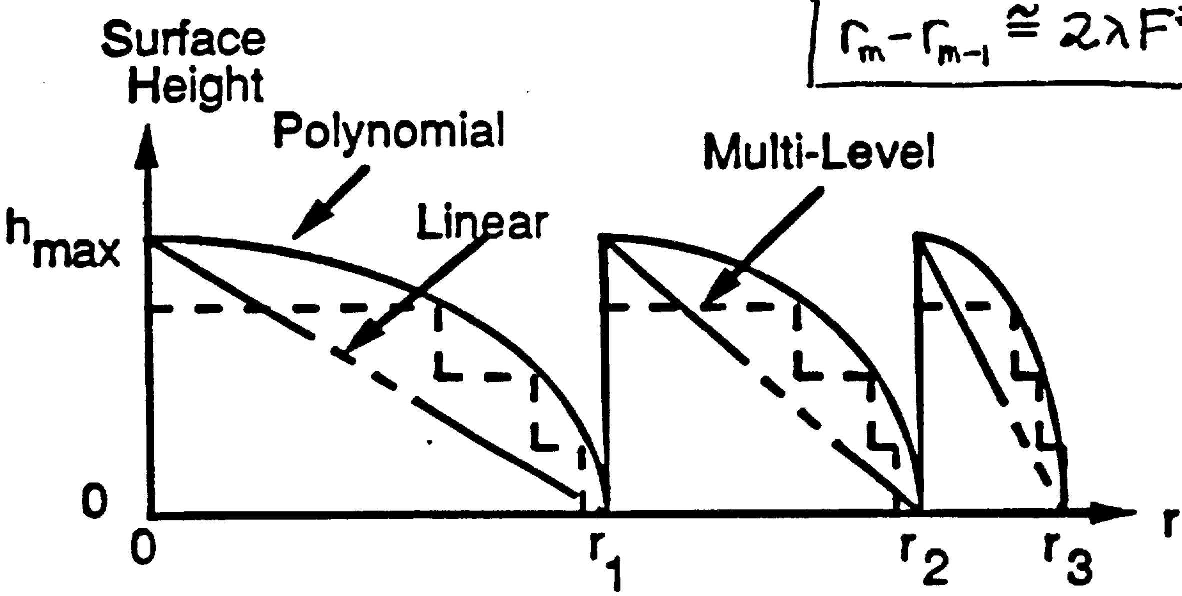
Athermalization of Optical Systems

Diffractive Lenses

- Phase Function of Lens

$$\phi(r) = 2\pi(A\,r^2 + G\,r^4 + \cdots)$$

$$\boxed{r_m - r_{m-1} \cong 2\lambda F^{\#}}$$



- 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)

Blaze	Peak Efficiency
Polynomial	100 %
Linear	99 %
16 level	98.7 %
8 level	95 %
4 level	81.1 %

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

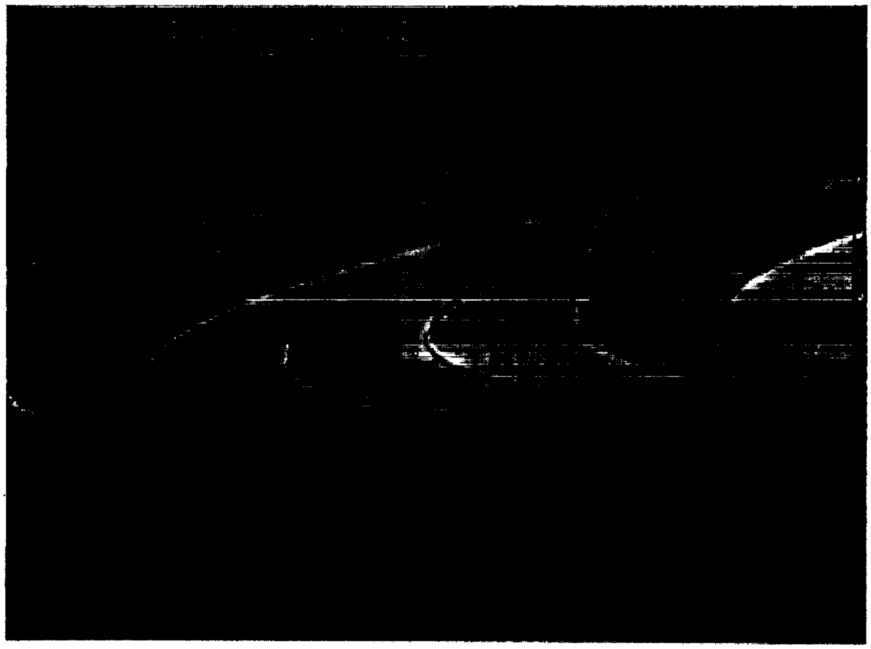
Replication Methods

Compression Molding

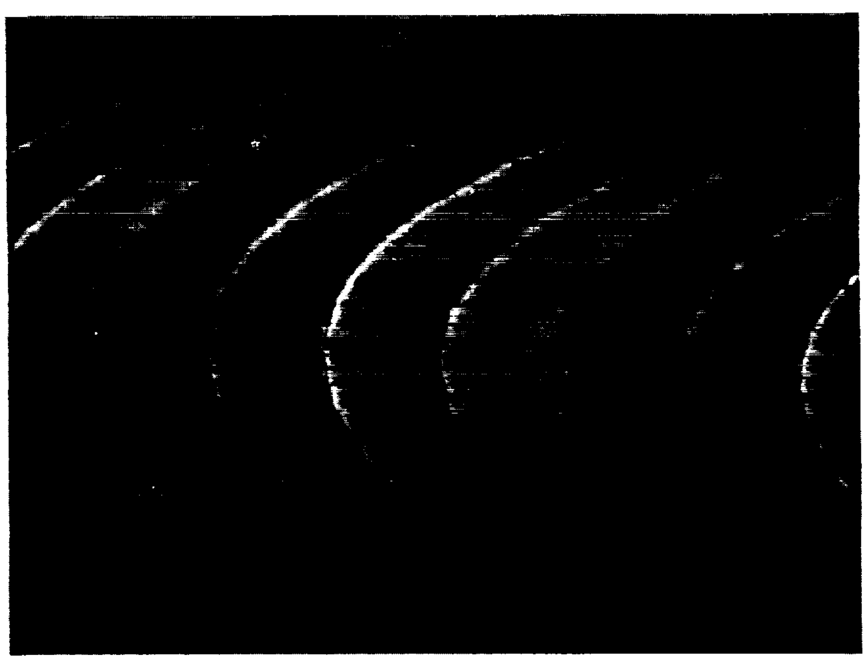
Cast and Cure Methods

(excellent temperature &
mechanical properties)

Binary Optics Lens
4-Level



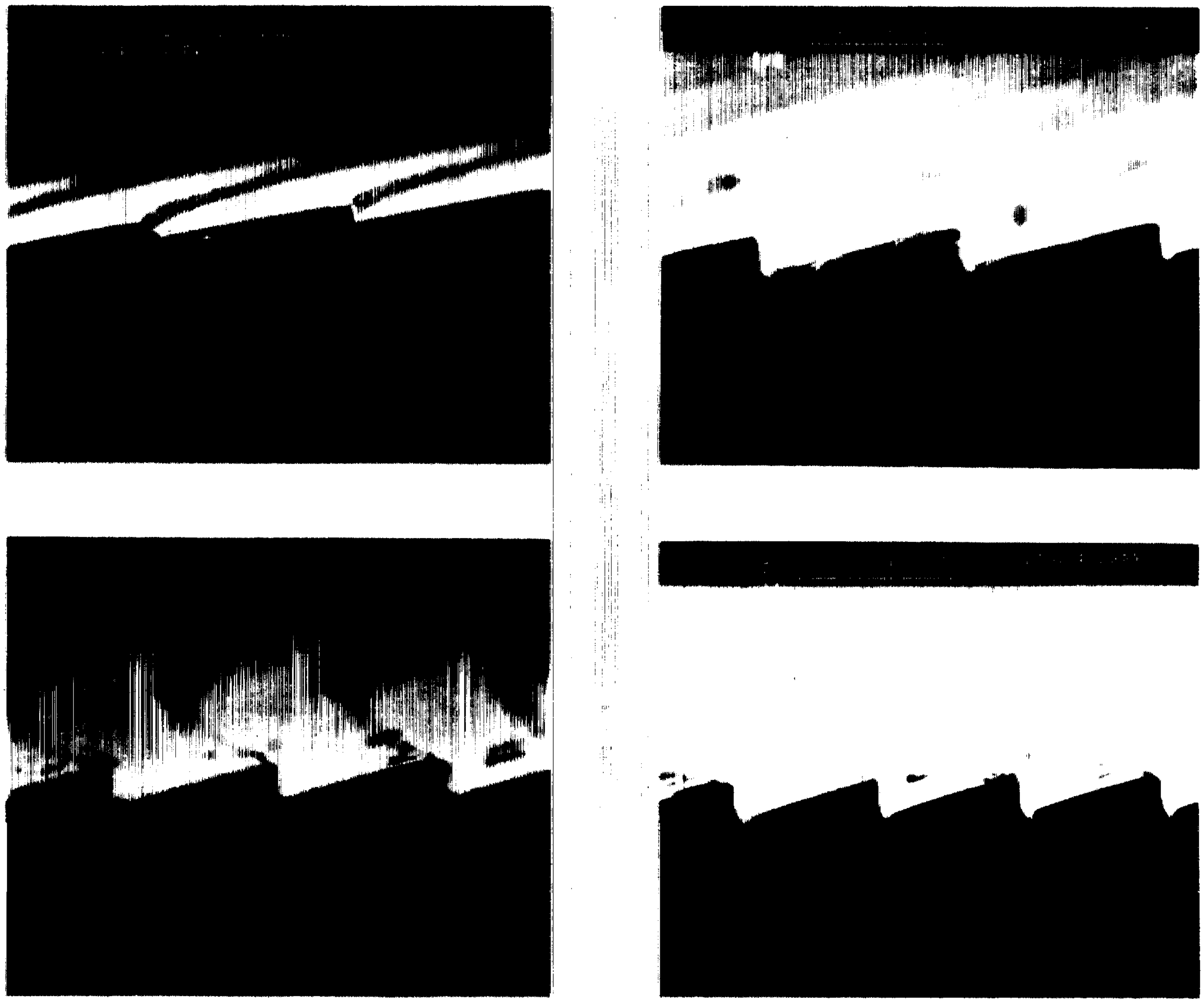
Etched Silicon Master



Electro-Formed Nickel Master

Blazed Diffractive Lens

F.L. = 75 mm, f/#3, λ_0 = 587.6 nm



RPC

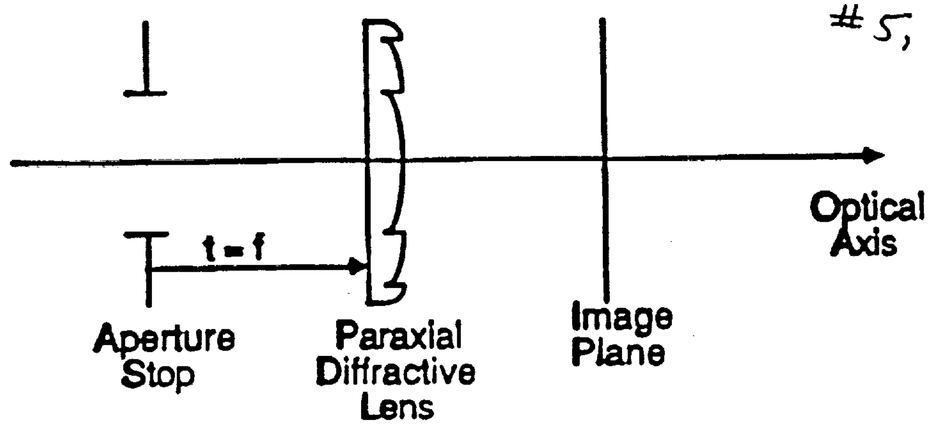
Laser Pattern Generator (Single-Point, X-Y)

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

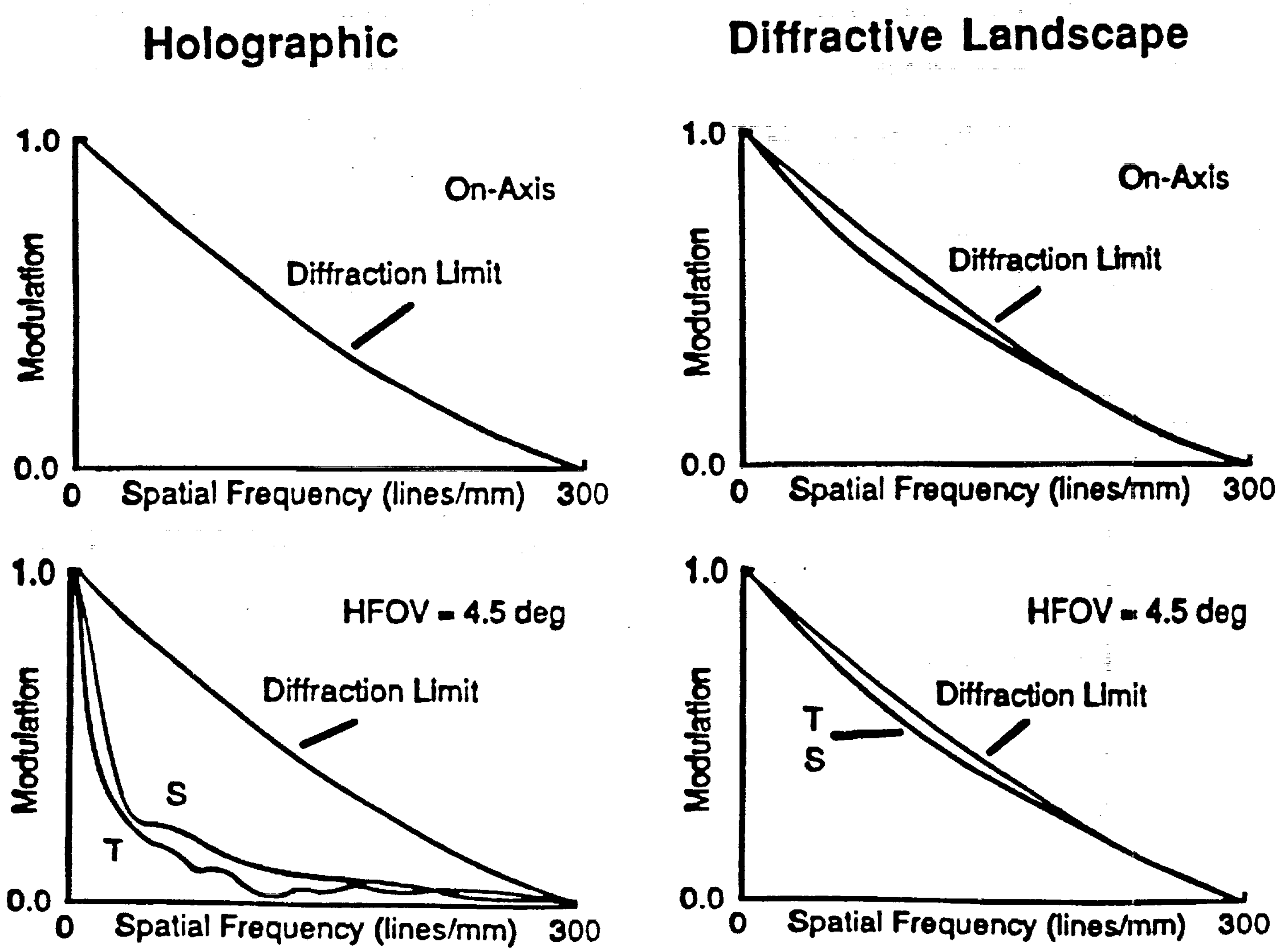
Diffractive Landscape Lens

US Patent #5,013,133



Modulation Transfer Functions

F/5.6 F = 50 mm λ_0 = 587.6 nm



Achromatic Doublet

- Lens Powers

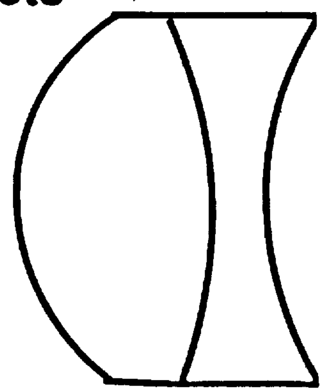
$$\phi_a = \frac{V_a}{V_a - V_b}\Phi$$

- Abbe numbers

$20 < V_{glass} < 90$

$V_{DOE} = -3.45$

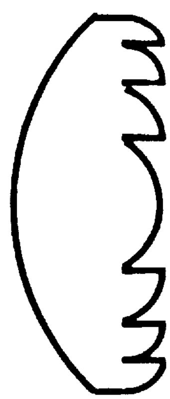
- **Conventional Doublets**



crown $V_a = 60$, $\phi_a = 2.5\Phi$

flint $V_b = 36$, $\phi_b = -1.5\Phi$

- **Hybrid doublet**



crown $V_a = 60$, $\phi_a = 0.95\Phi$

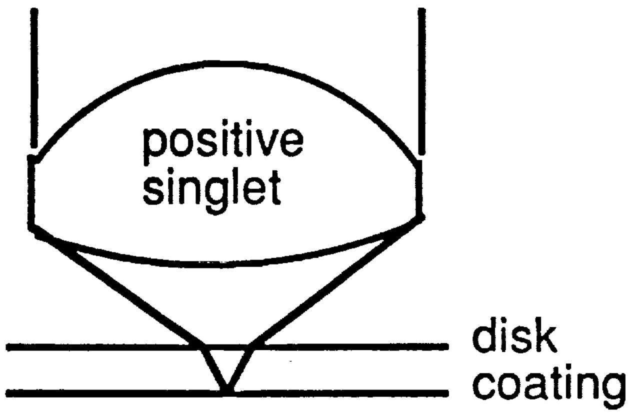
DOE $V_b = -3.45$, $\phi_b = 0.05\Phi$

- 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

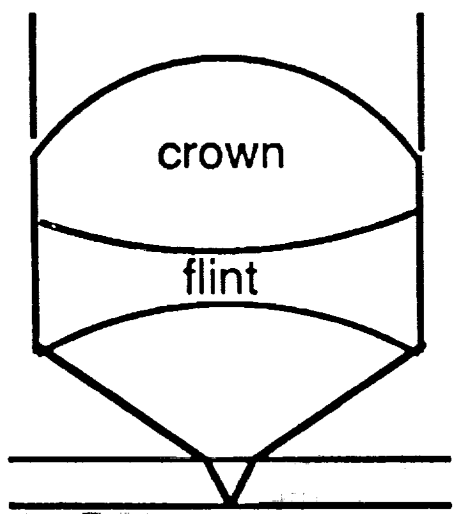
$f \approx 3.0$mm

HFOV = 1°

$\lambda_o = 0.780 \pm 0.01\mu m$

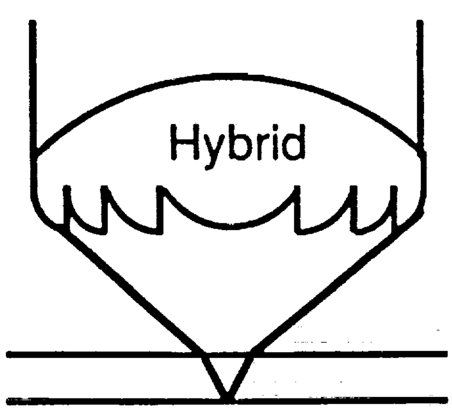
monochromatic

- Conventional Glass Doublet



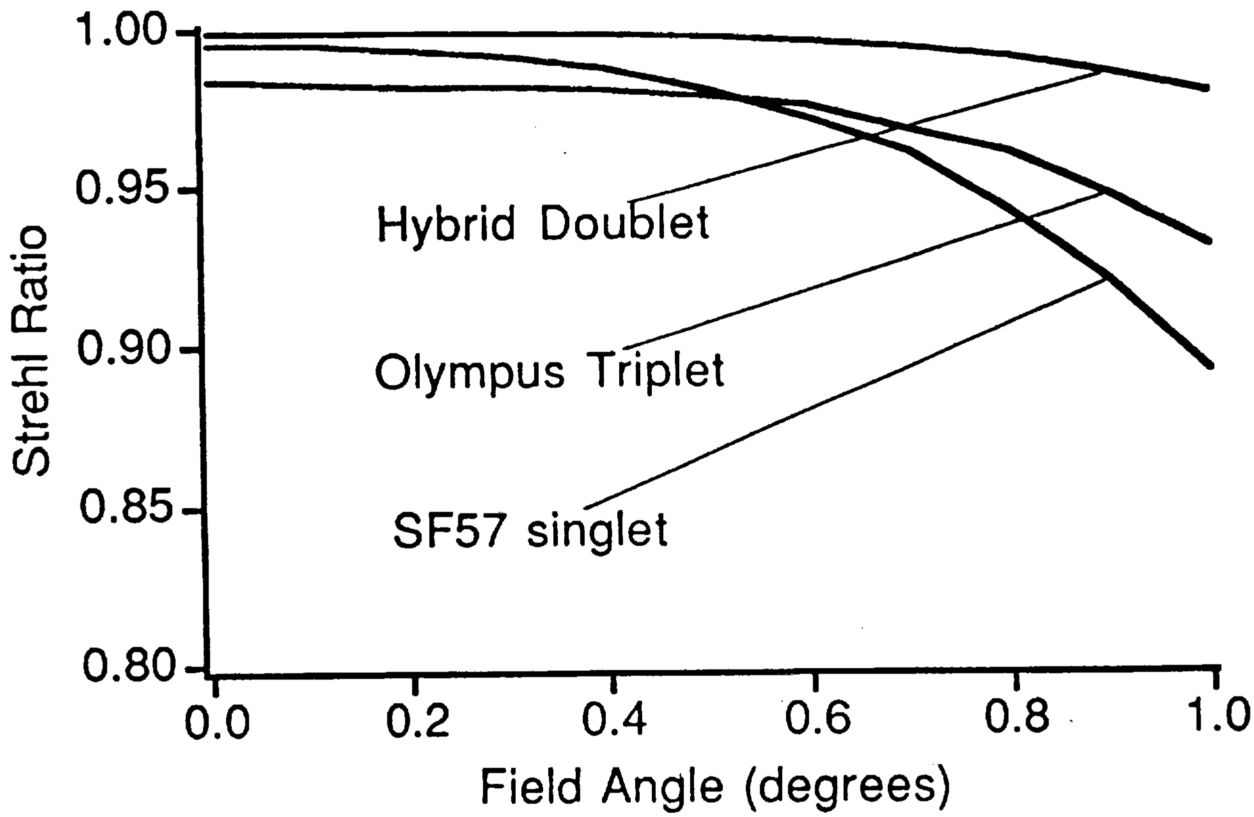
Conventional achromatic doublet adds weight and size

- Hybrid Doublet



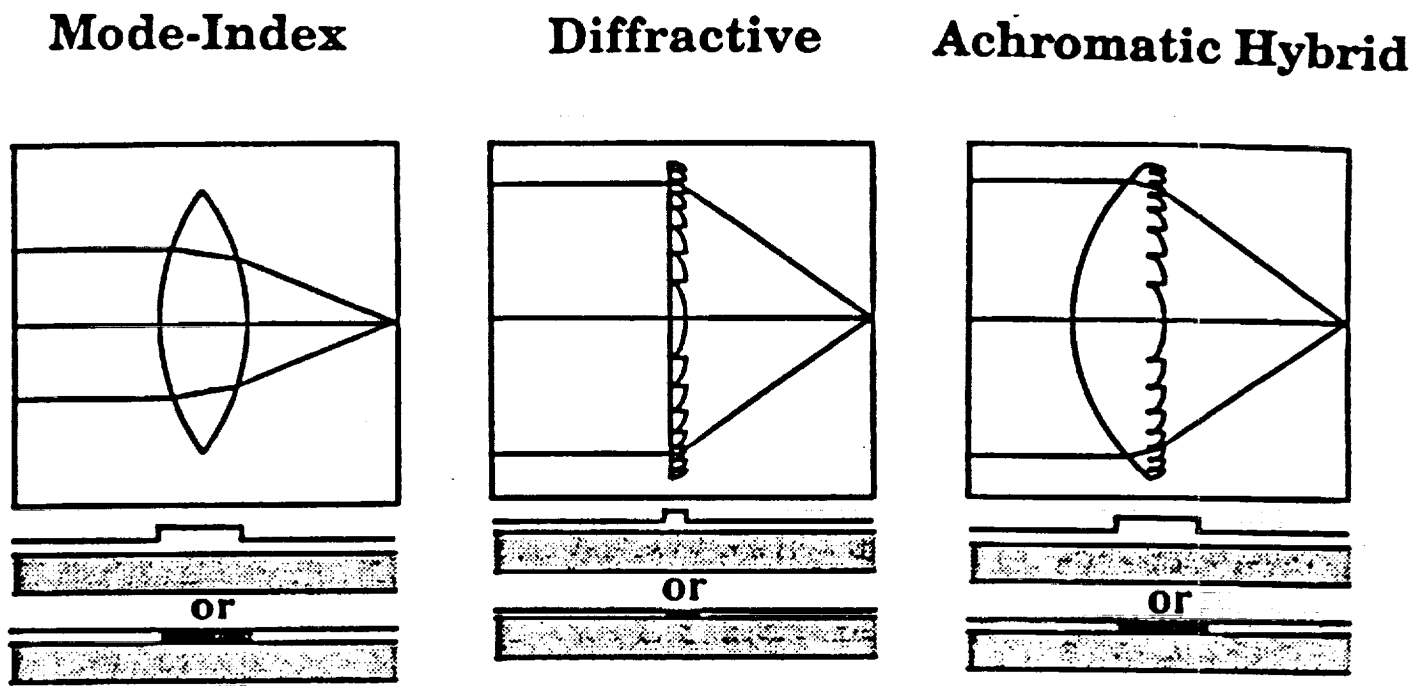
Hybrid lens reduces weight, and helps correct other aberrations

Strehl Ratio vs Field Angle

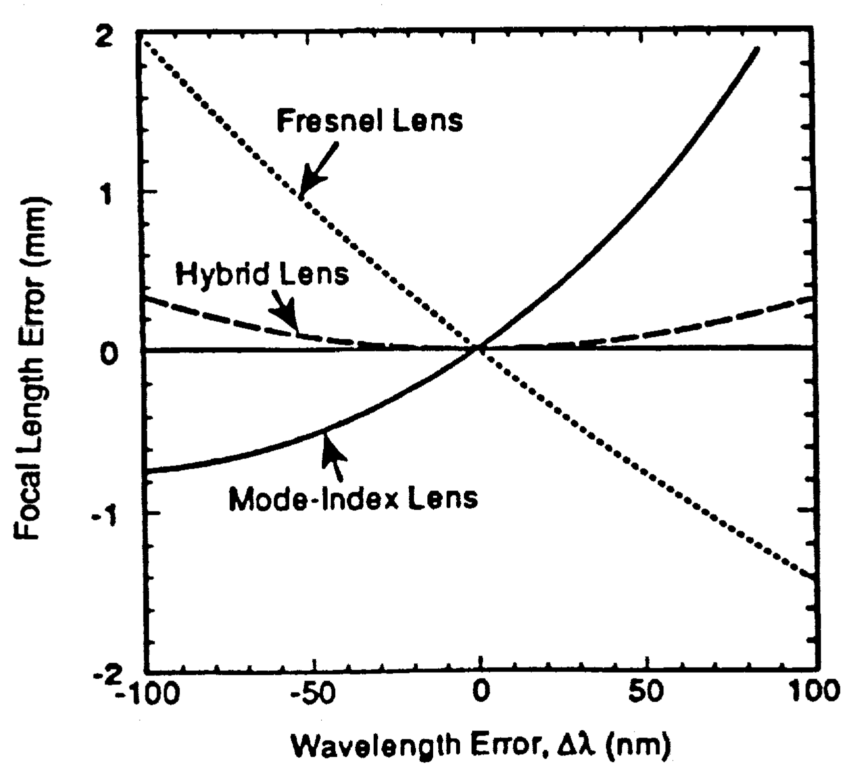


- Numerical Apertures:
  - Hybrid Doublet - 0.57
  - Olympus Triplet - 0.50
  - SF57 Singlet - 0.53

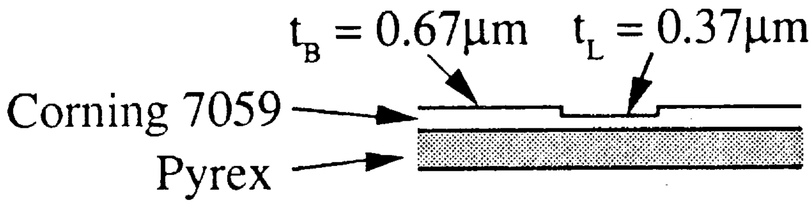
Waveguide Lenses



Longitudinal Chromatic Aberration

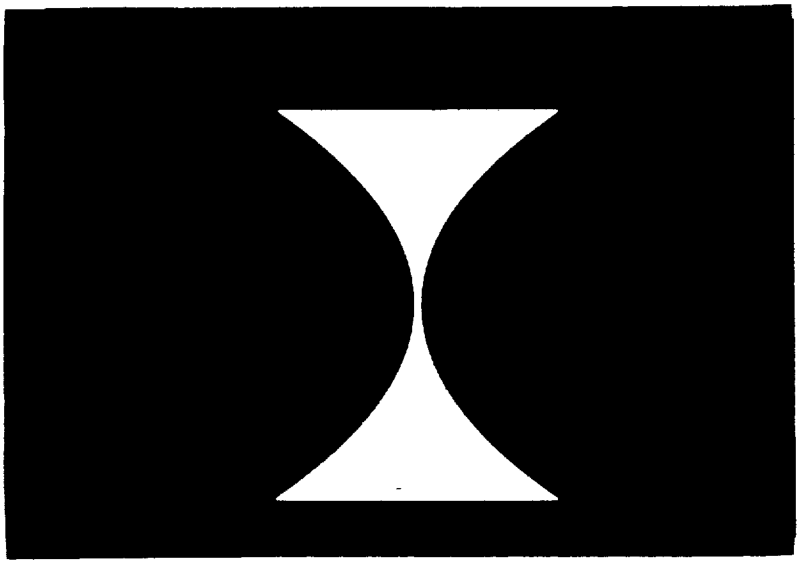


Waveguide Lens Comparison

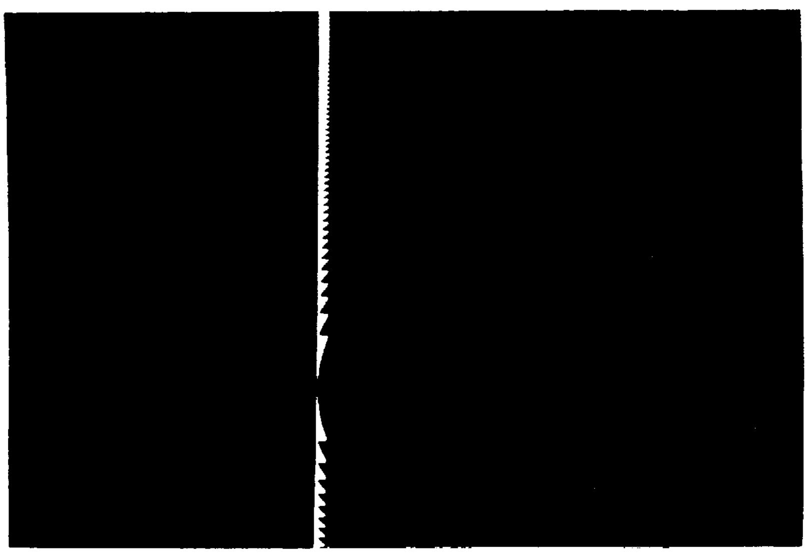


$N_B = 1.532$, $N_L = 1.497$
$\Delta N = -0.035$

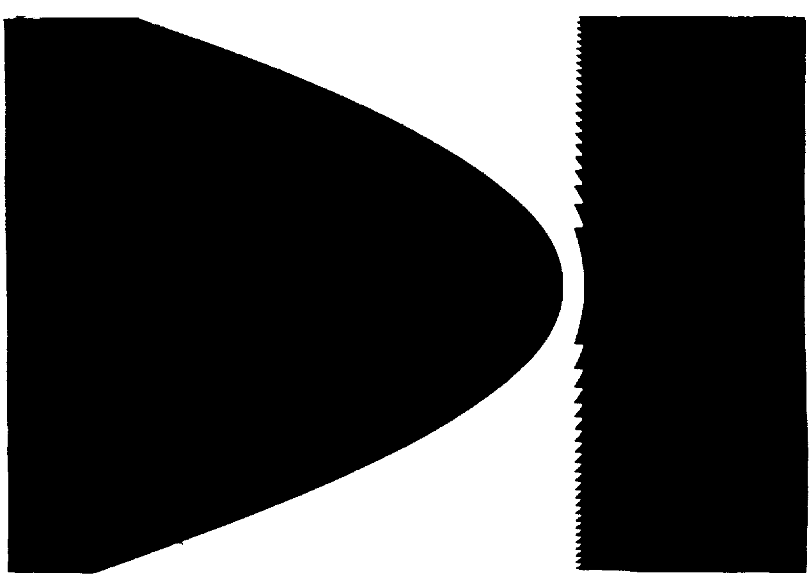
focal length = 10mm, F/5



Mode-Index Lens



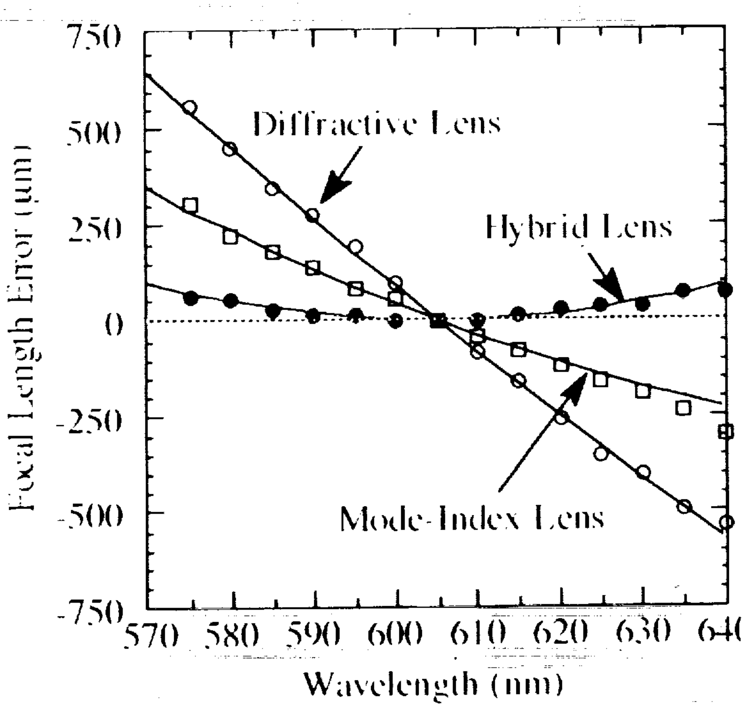
Diffractive Lens
$h_0 = 17.5\mu m$
zones = 54
smallest zone = $6.1\mu m$



Hybrid Achromatic Lens
Mode-index surface
$f_{mi} = 5.3mm$
Diffractive surface
$f_d = -11.5mm$
$h_0 = 17.5\mu m$
zones = 47
smallest zone = $7.0\mu m$

Waveguide Lens Performance Comparison

	Insertion Loss	Diffraction Efficiency
Mode-Index Lens	40%	—
Diffractive Lens	40%	70%
Hybrid Achromatic Lens	40%	70%



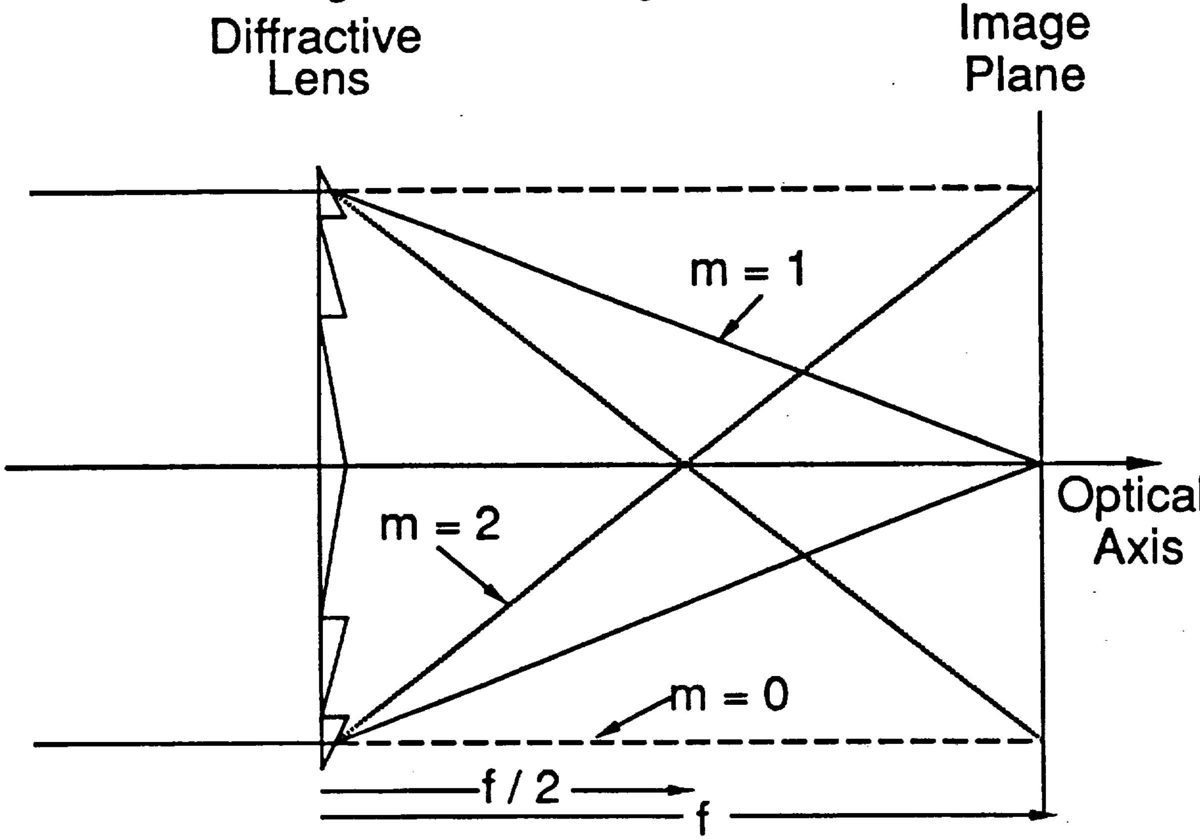
Wavelength Range for Strehl Ratio > 0.8

(Depth of focus = 44 μm)

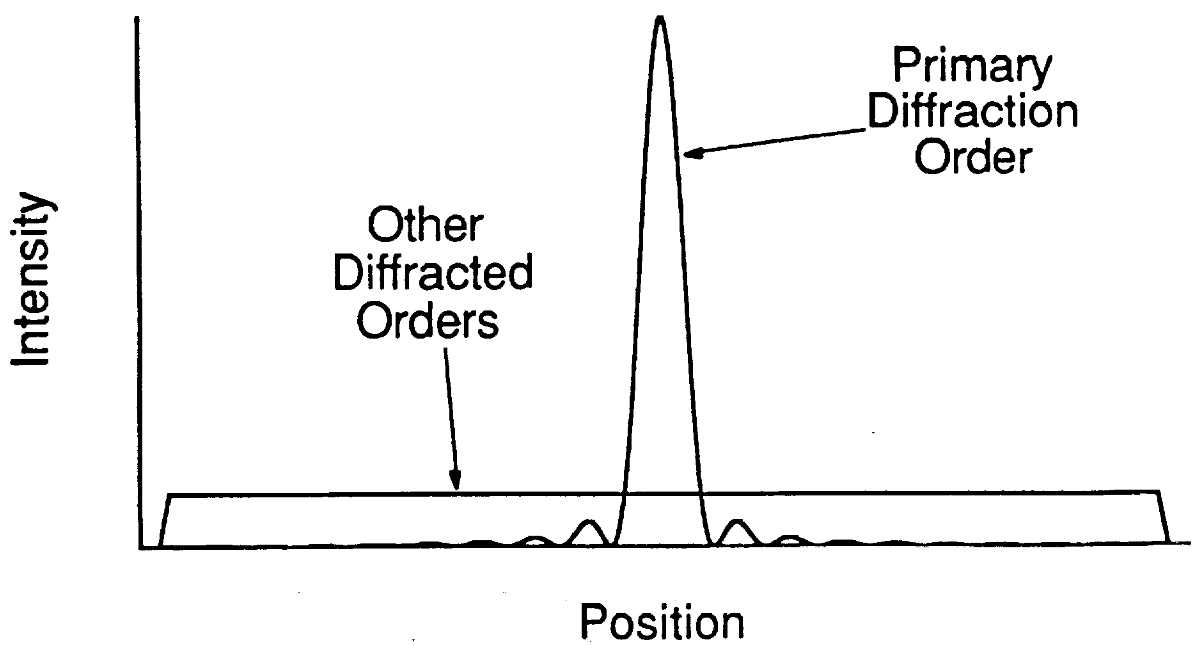
Mode-Index: 11 nm
Diffractive: 5 nm
Hybrid: 49 nm

Diffractive Lens Imaging

- Undiffracted light forms background in image plane



- Point Spread Function



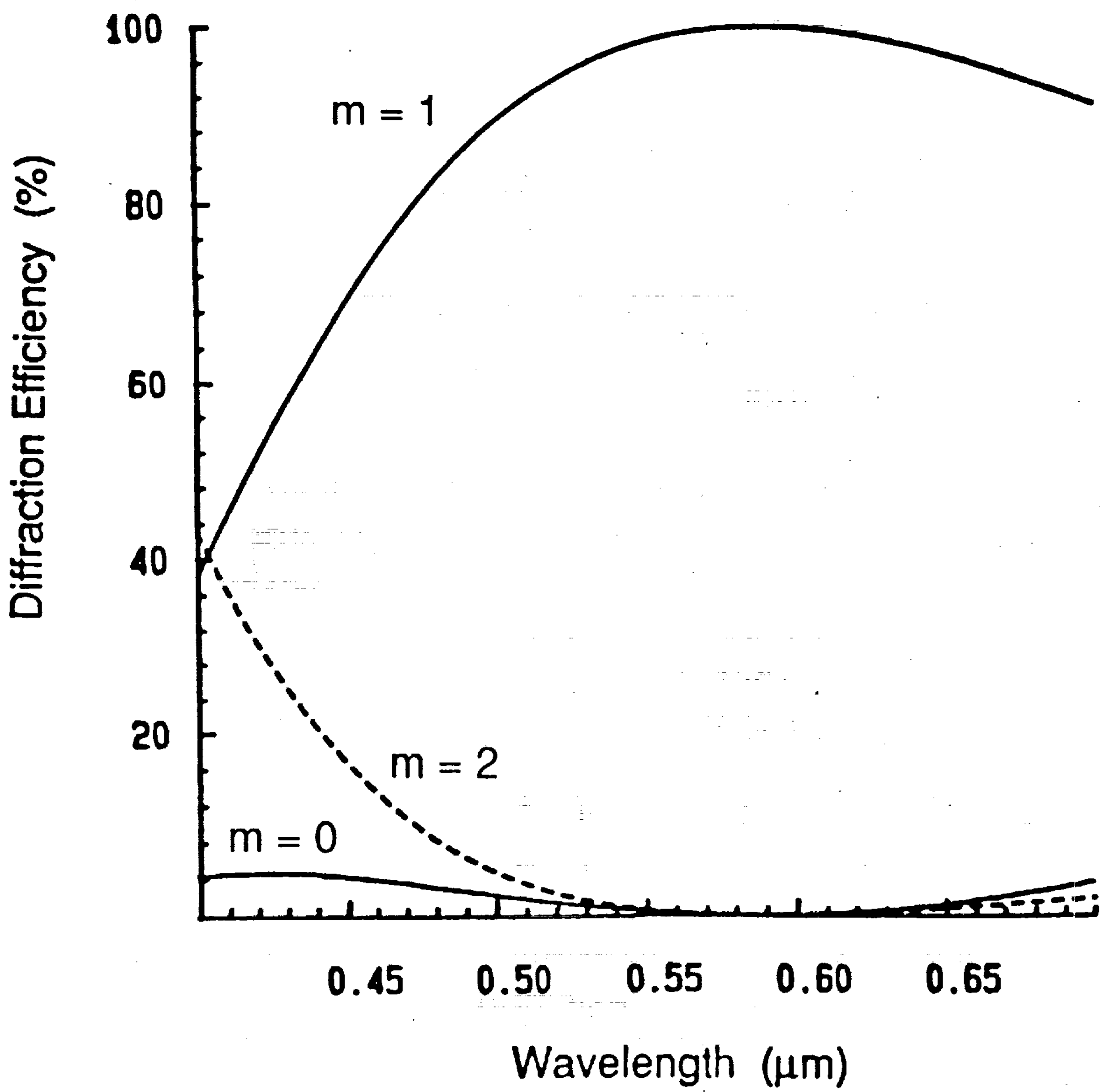
Diffraction Efficiency

- Analytic result for diffraction efficiency

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

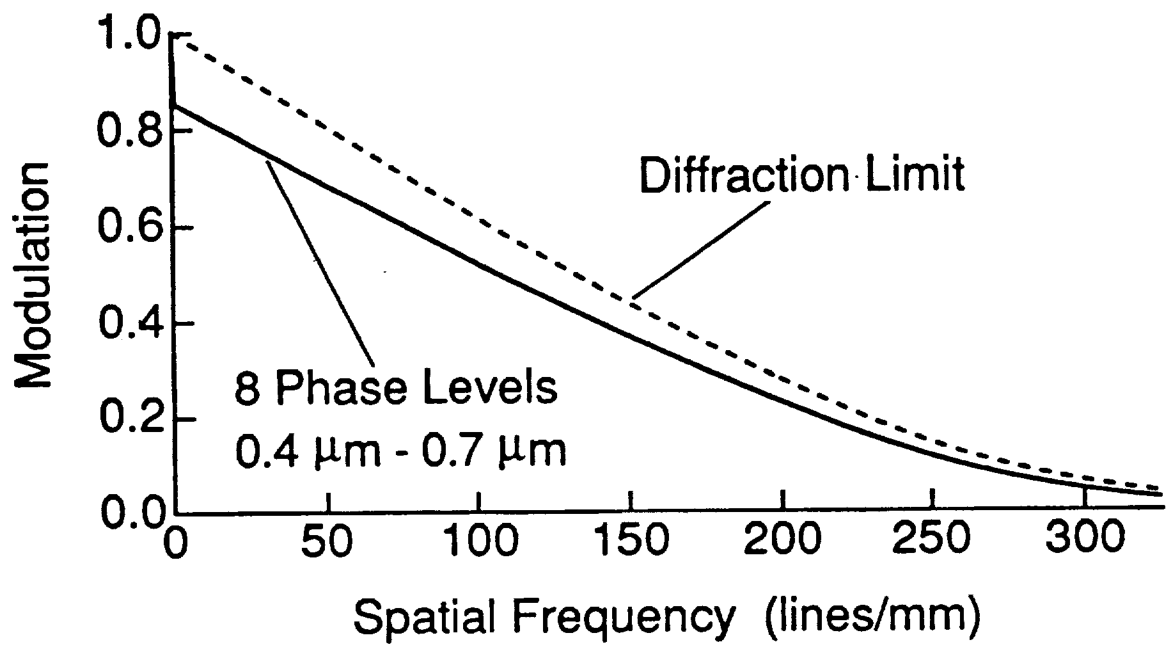
- Wavelength detuning parameter

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

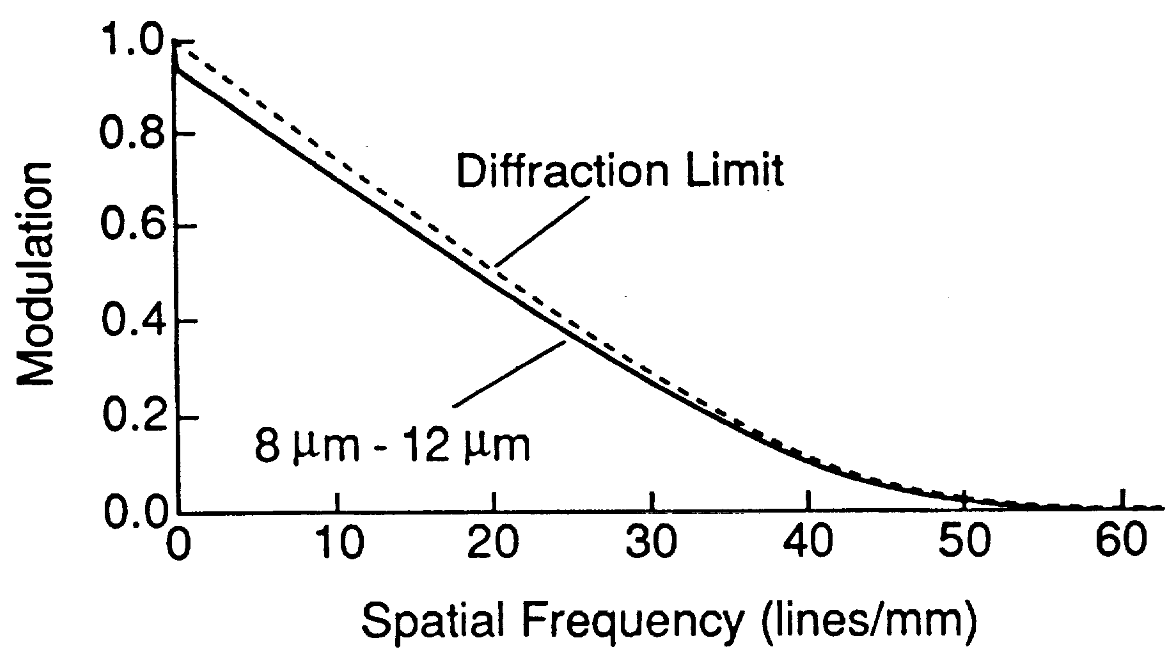


Polychromatic Examples

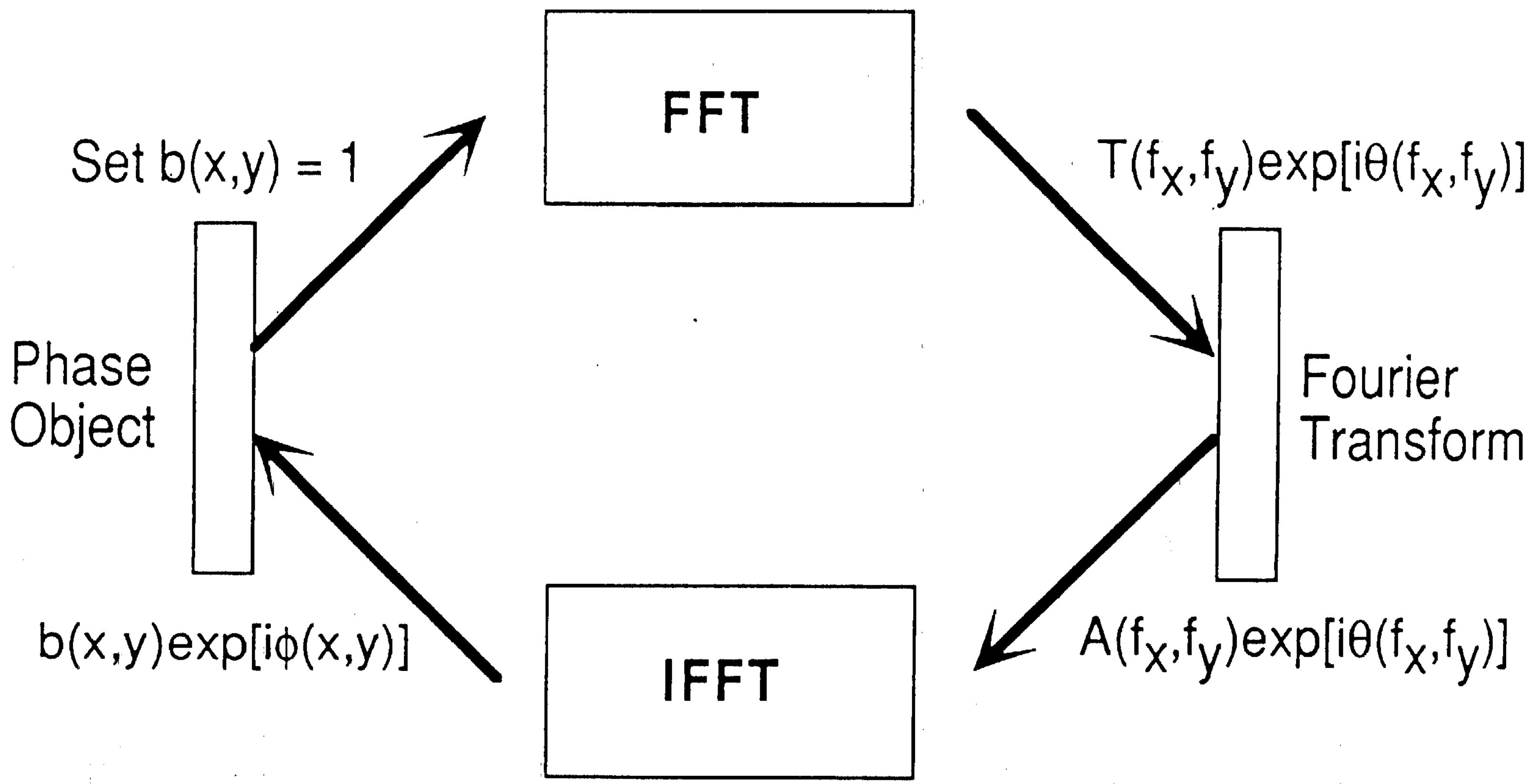
- $\lambda_0 = 0.55\ \mu m$ $\lambda_{min} = 0.4\ \mu m$ $\lambda_{max} = 0.7\ \mu m$
  P = 8 F/5.6 $\eta_{int,poly} = (0.95)(0.914) = 0.868$



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



Synthesis of Phase Gratings From Known Fourier Modulus Data

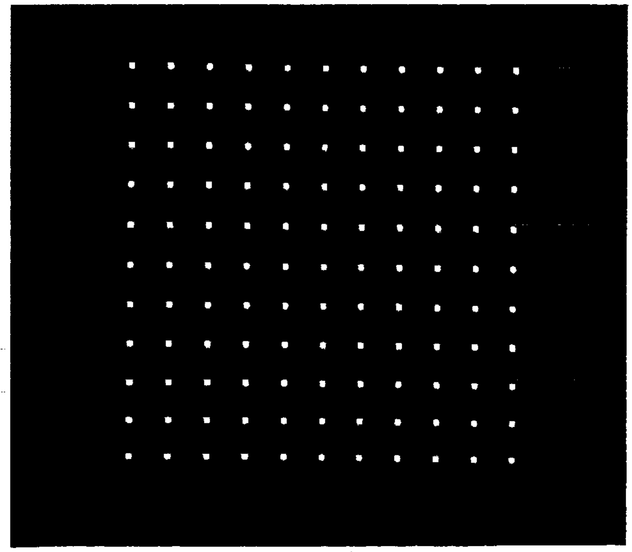


$A(f_x,f_y)$ = Desired Fourier Modulus

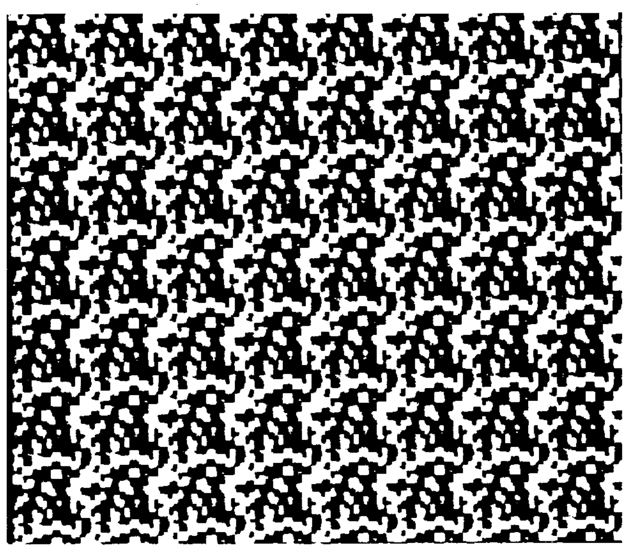
Phase Grating Synthesis

11 x 11 Array, Equal Intensity Diffracted Orders

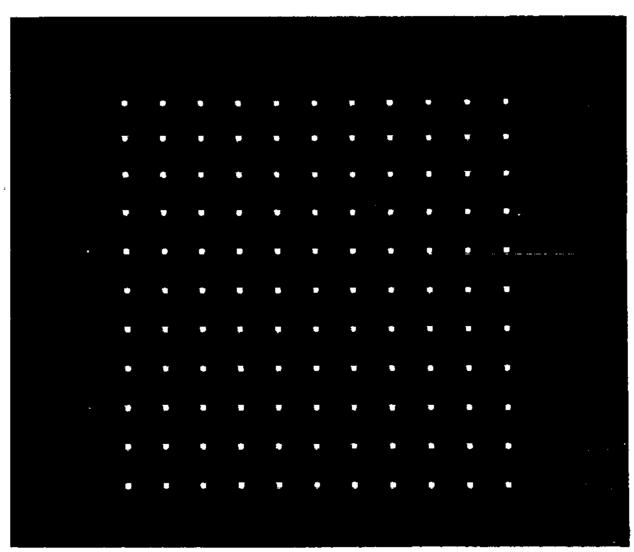
Desired Fourier Modulus



Phase Grating



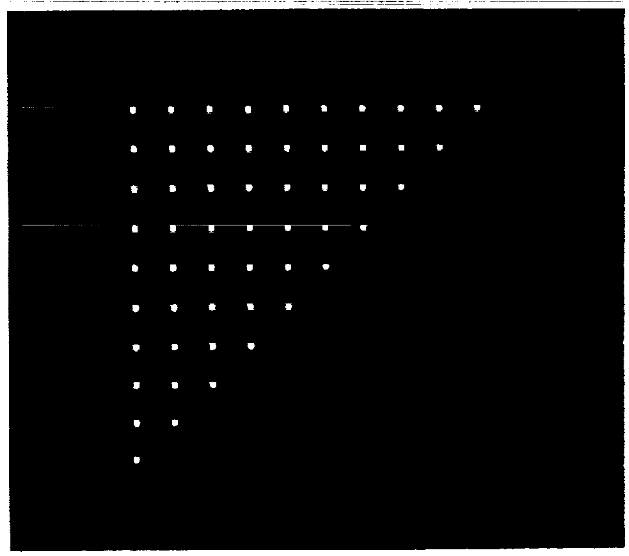
Reconstructed Fourier Modulus



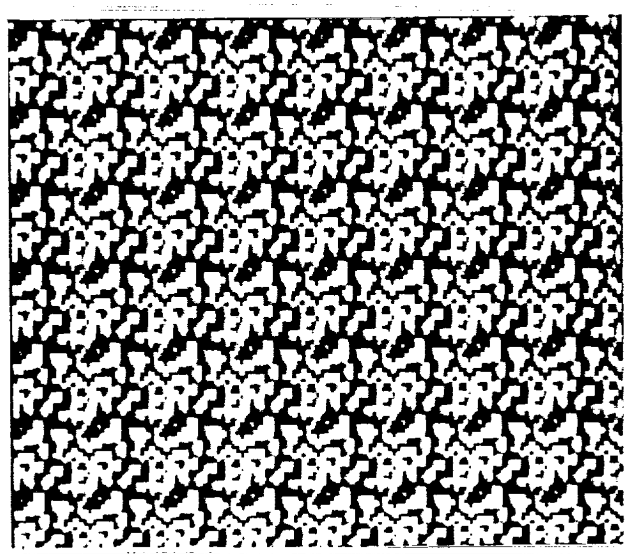
Phase Grating Synthesis

Triangular Array, Equal Intensity Diffracted Orders

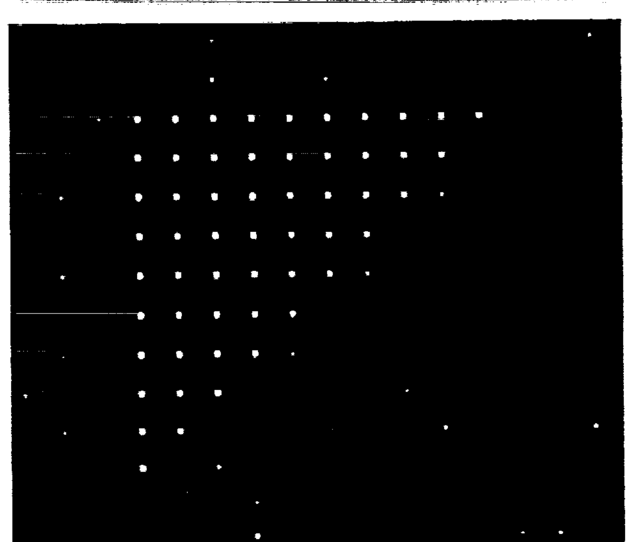
Desired Fourier Modulus



Phase Grating



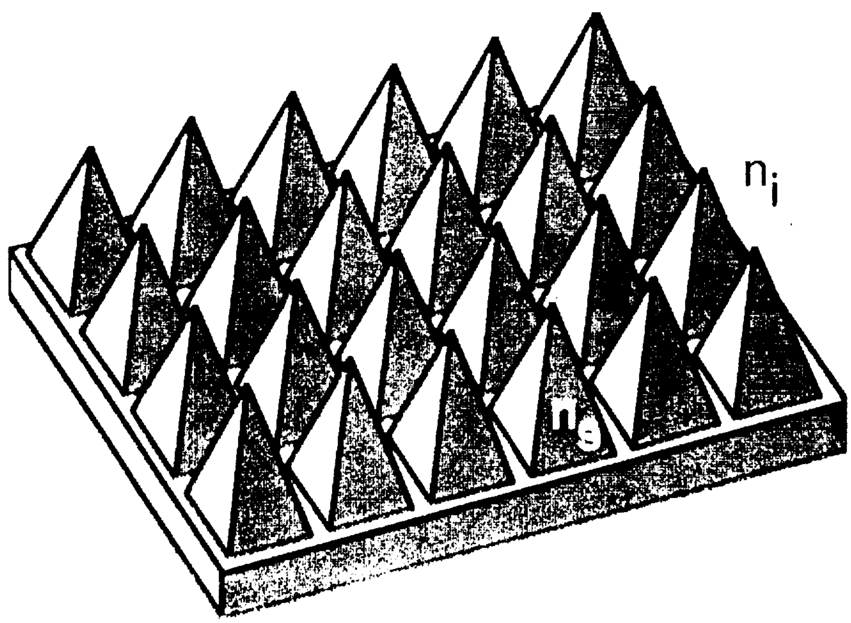
Reconstructed Fourier Modulus



Sub-Wavelength Structured Surfaces

Concept

Use surface structure (small compared to the illumination wavelength) to *synthesize* an effective index of refraction



Approach

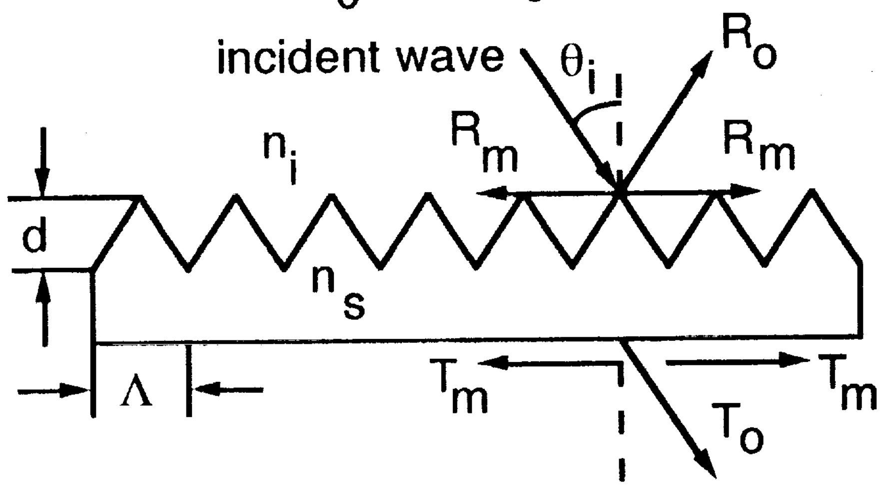
Effective Medium Theory
Rigorous Electromagnetic Theory
Tapered Transmission-Line Theory
Fabricate using Photolithographic Techniques

Features

Supression of Fresnel Reflections
Large Field-of-View and Spectral Bandwidth
Advantages over Thin Film Coatings
 No Cohesion Problems
Birefringent Surface

ARS Surfaces

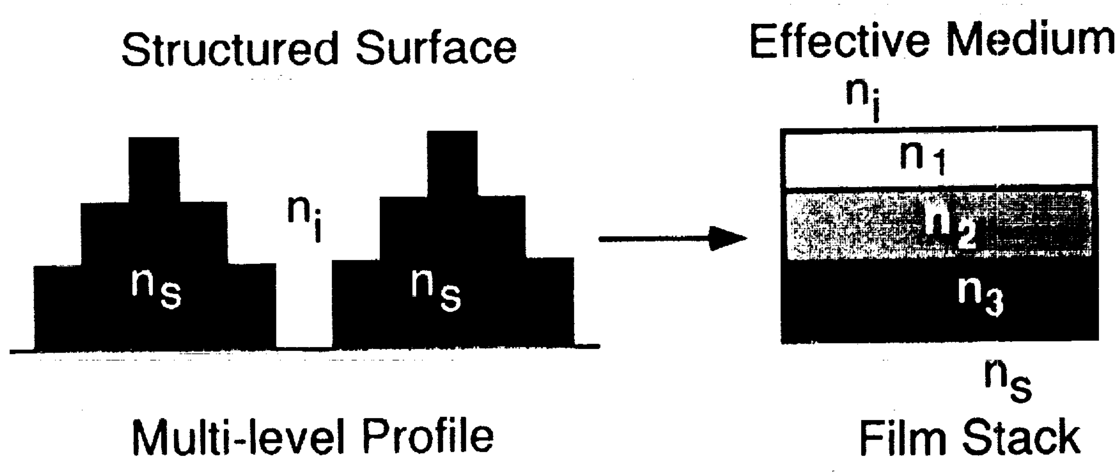
- Require *ONLY* R_0 and T_0 non-evanescent



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

- Period Λ smaller than wavelength λ

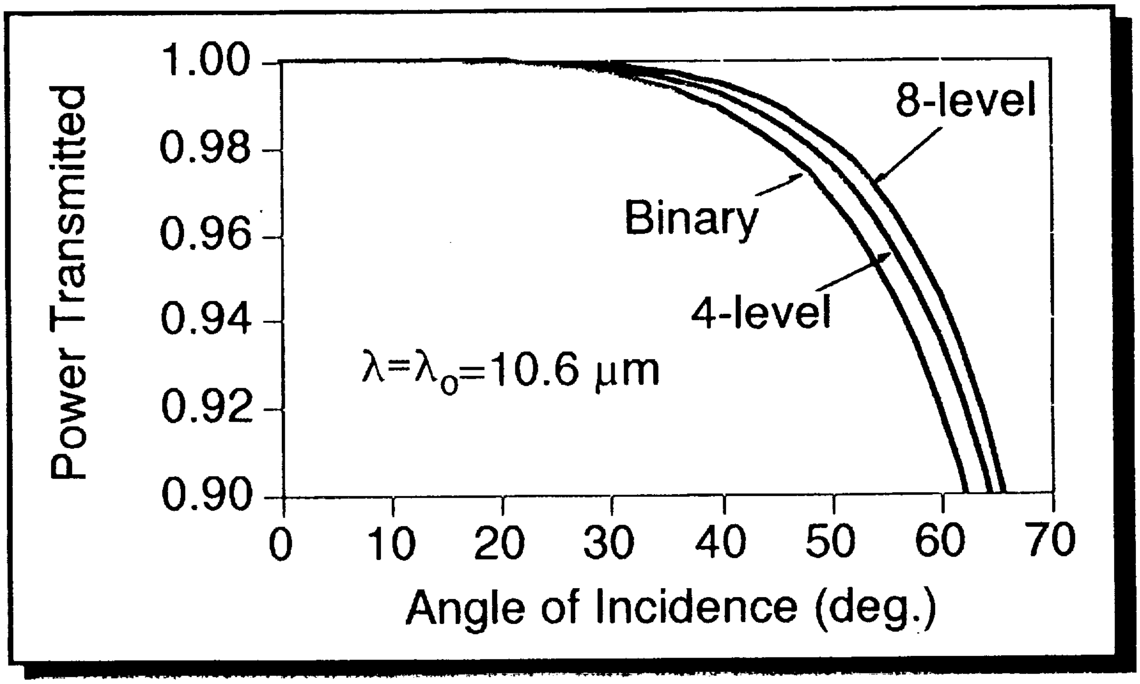
Effective Medium Theory (EMT)



- Light averages optical properties of structured region

Angle of Incidence Sensitivity of GaAs 2-D Multilevel ARS Surfaces

- **Performance for randomly-polarized radiation**

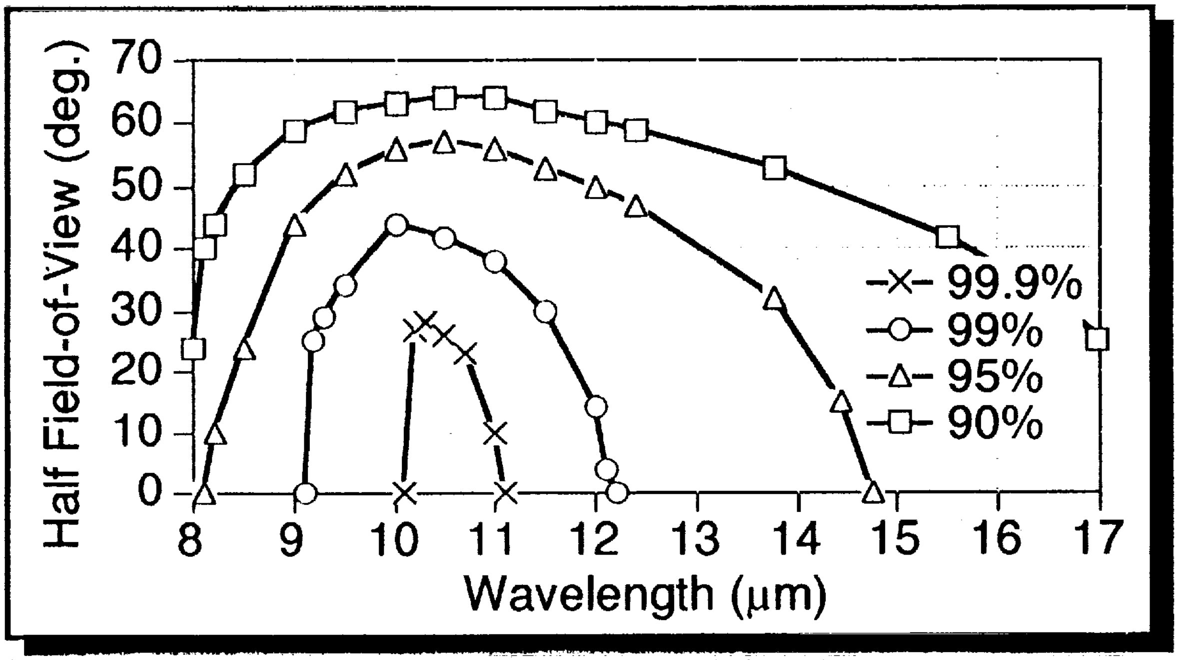


- **ARS Surface Parameters**

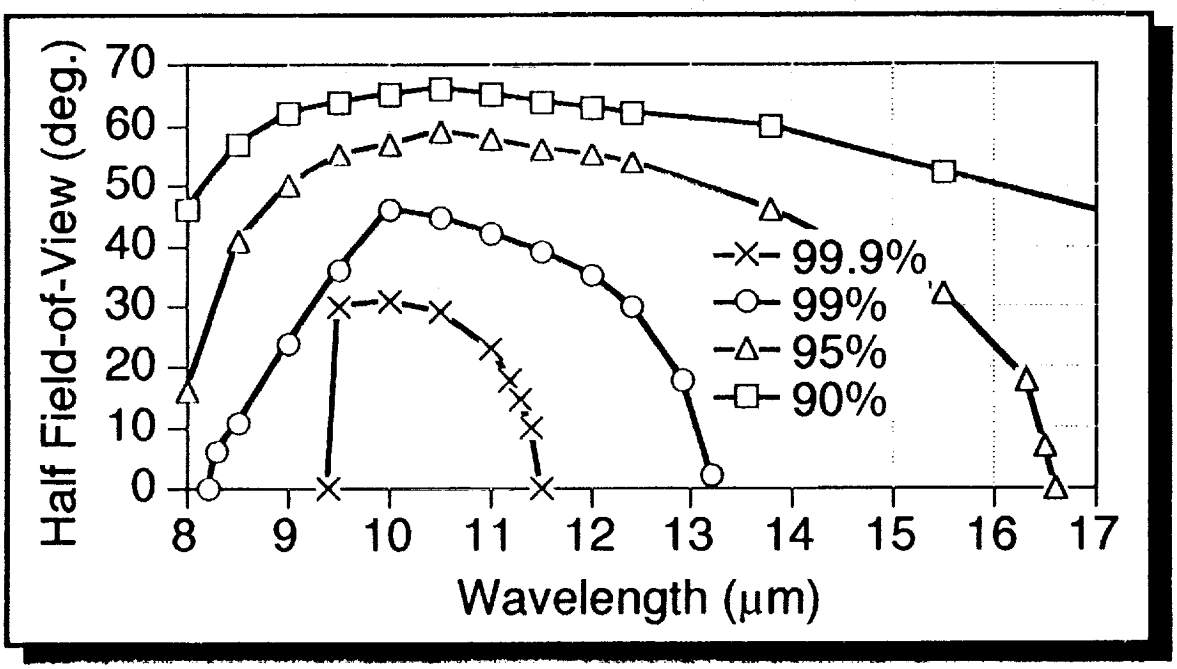
$n_i=1$, $n_s=3.27$, $\Lambda_x=\Lambda_y=2.480\mu m$		
Profile	Profile depth (μm)	Duty Cycle (%)
Binary	1.463	69.7
4-level	3.244	91.7
8-level	4.441	98.5

Spectral Sensitivity of GaAs 2-D Multi-level ARS Surfaces

- **4-level Pyramidal Profile**



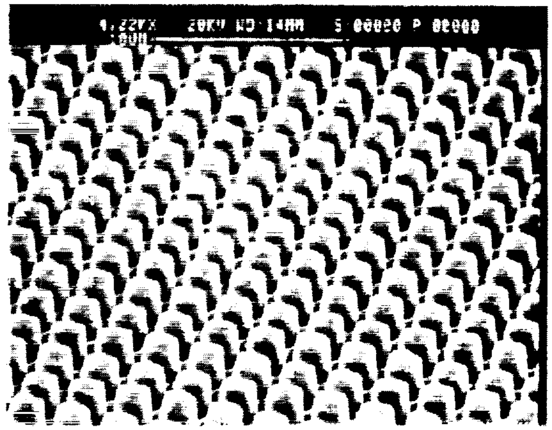
- **8-level Pyramidal Profile**

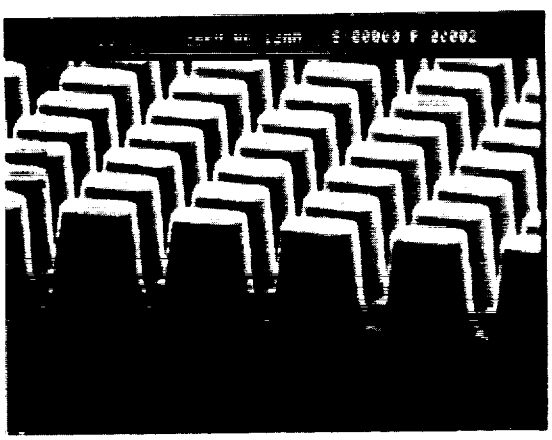


Experimental Work
2-D Binary ARS Surface for GaAs

- Preliminary Results: CAIBE etched GaAs

4.22k Magnification





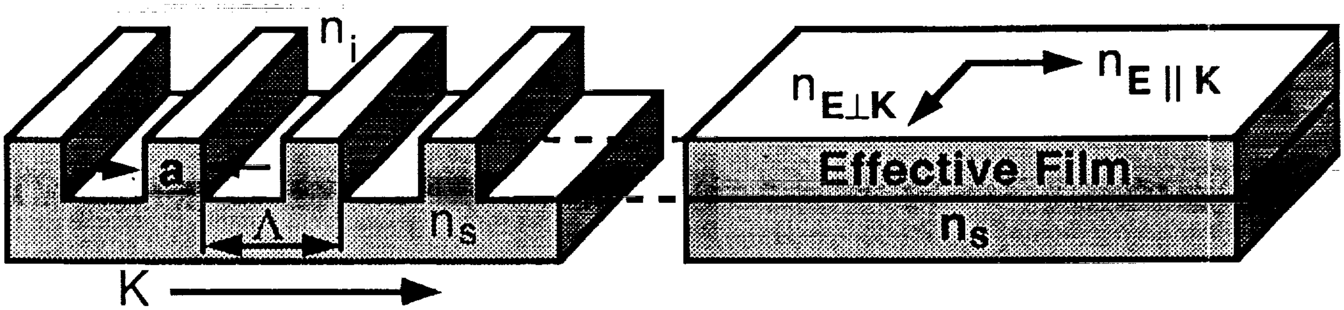
10.00k Magnification

16.50k Magnification

Surfaces Fabricated at Cornell's National Nanofabrication Facilities (NNF)

Polarization Components using Form Birefringence

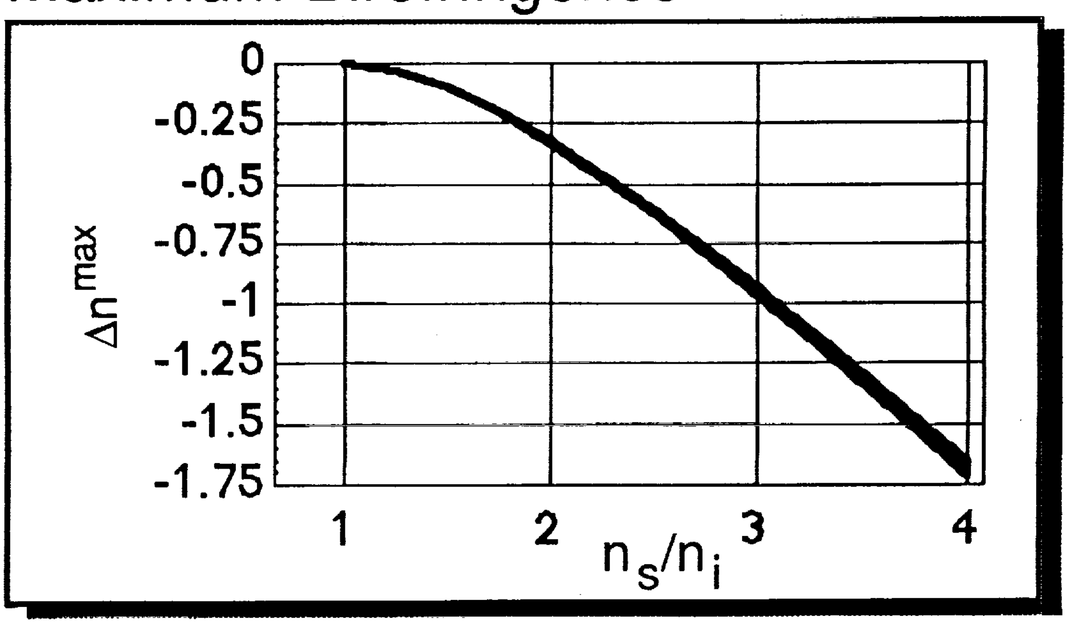
- High-Frequency Surface-Relief Gratings



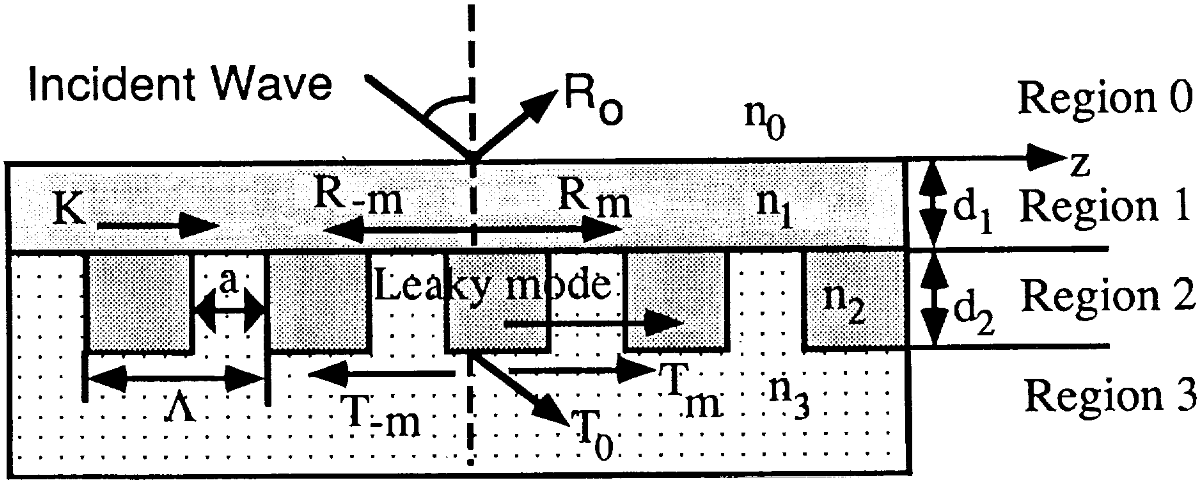
- Birefringence = $\Delta n = n_{E\perp K} - n_{E||K}$
- Δn is a function of filling factor f

$$f = a/\Lambda$$

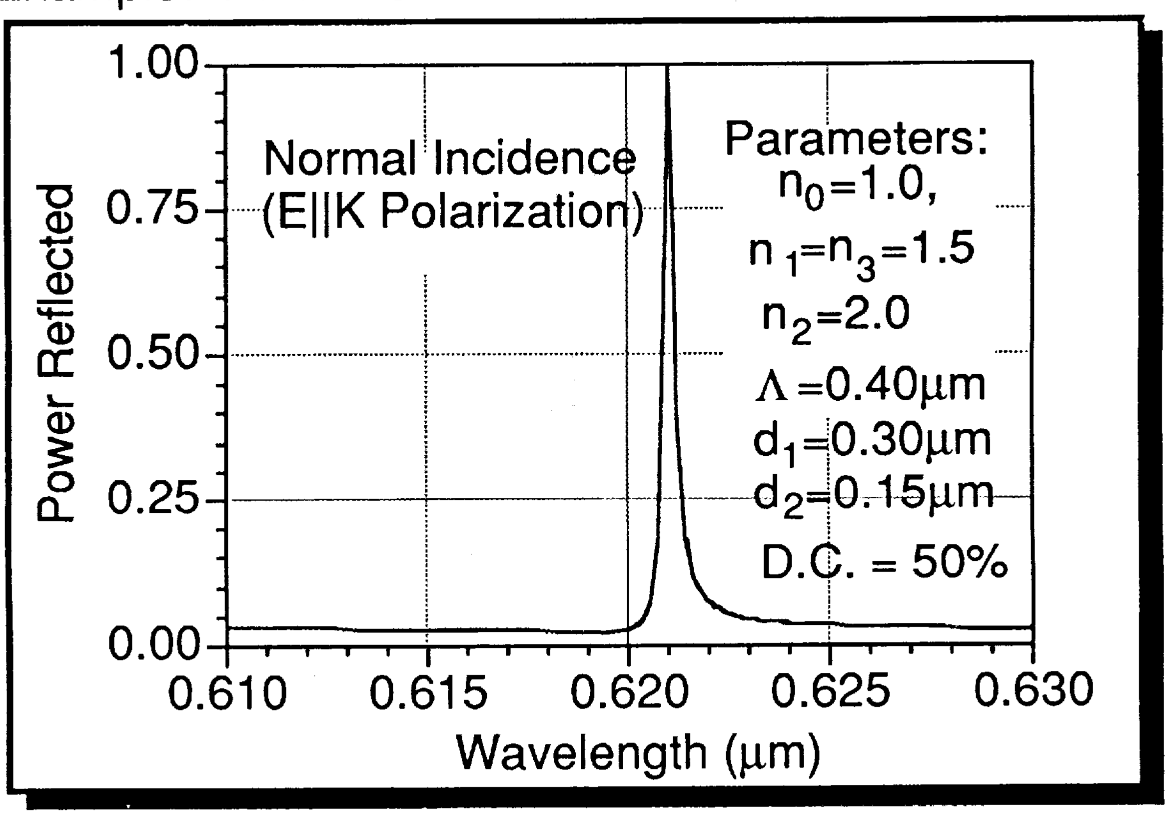
- Maximum Birefringence



Resonance Structures



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



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