Electron-Beam Fabrication of Gray-Scale Occulting Spots in High-Energy Beam Sensitive (HEBS) Glass

ECLIPSE

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Introduction

Objective

- Fabricate gray-scale occulting spots for coronographic telescopes

Approach

- Electron-beam exposure of high-energy beam sensitive (HEBS) glass (product of Canyon Materials, Inc., San Diego, CA)
  - Calibrate transmittance of HEBS glass (measure optical density as a function of electron dose and acceleration voltage)
  - Determine strength and functional form of E-beam proximity effect (exposure due to scattered electrons)
  - Determine limitations imposed by E-beam lithography system (job file parameter limits, clock quantization,)

Introduction

What we have learned so far

- HEBS glass can be darkened to optical density 8 (OD 7.66 achieved without saturation)
  - Requires extra thick sensitive layer (~10 μm) and 100kV electron exposure
  - Optical density vs. E-beam dose can be calibrated accurately
  - There is significant graying around the primary exposure due to scattered electrons ("proximity effect"). This has the *desirable* effect of smoothing the occulting spot profile.
- Electron-beam writing parameters can be selected to accurately represent the desired spot functions
  - Dose quantization error << 1% at high doses, <1% at low doses
- Need to improve occulting spot characterization techniques to enable accurate comparison of fabricated spots to desired functional forms
- Need to determine the effects of radiation on HEBS glass

Occulting Spot Specifications

Desired Specifications

- Minimum transmittance at center of spot
  - Intensity transmittance, $T < 10^{-8}$
  - Optical density, $OD = -\log(T) > 8$

- Functional form accuracy (Gaussian, sinc^2, etc.)
  - Amplitude transmittance error $< 1\text{x}10^4$ (under investigation)
  - Spatial pattern pixel size < wavelength (~800 nm) to avoid diffraction of light into planet detection regions

Electron-Beam Exposure of HEBS Glass

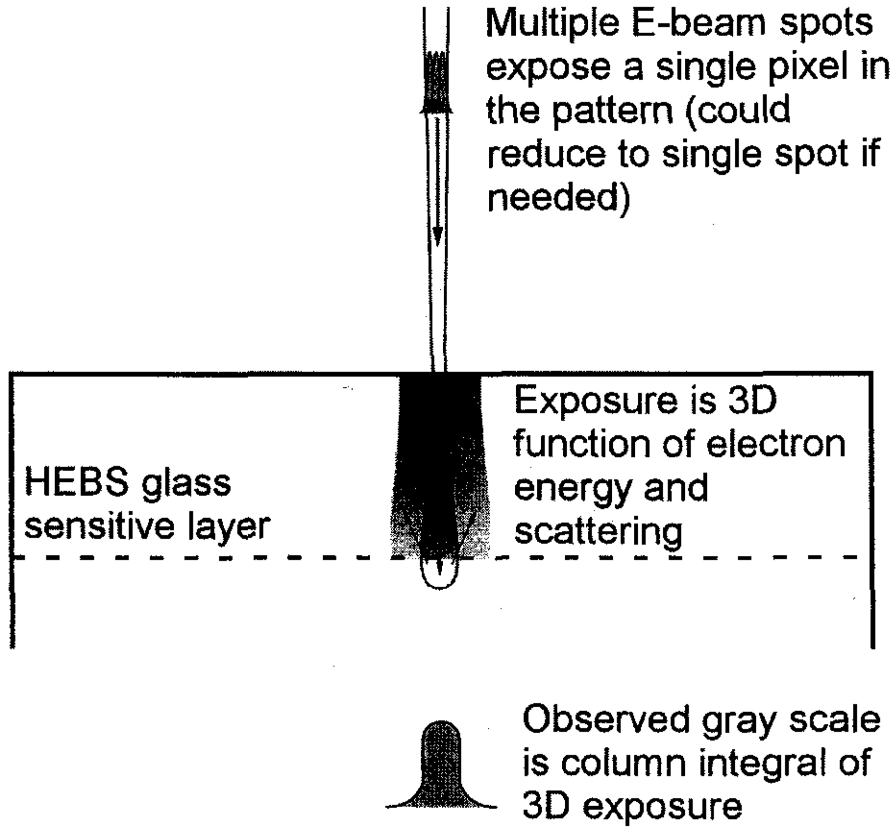
Gray-scale occulting spot fabrication method

- High energy beam sensitive (HEBS) glass ~~(product of Canyon Materials, San Diego, CA)~~
  - Low expansion zinc-borosilicate glass doped (ion-exchanged) with silver ion containing complex crystals and photo inhibitors
  - Silver ion complex crystals gray with electron-beam exposure
  - Sensitive layer is typically 3 μm thick
  - We ordered a special lot with sensitive layer ~10 μm thick to maximize optical density with 50 or 100 kV electron beam exposures

Electron-Beam Exposure of HEBS Glass

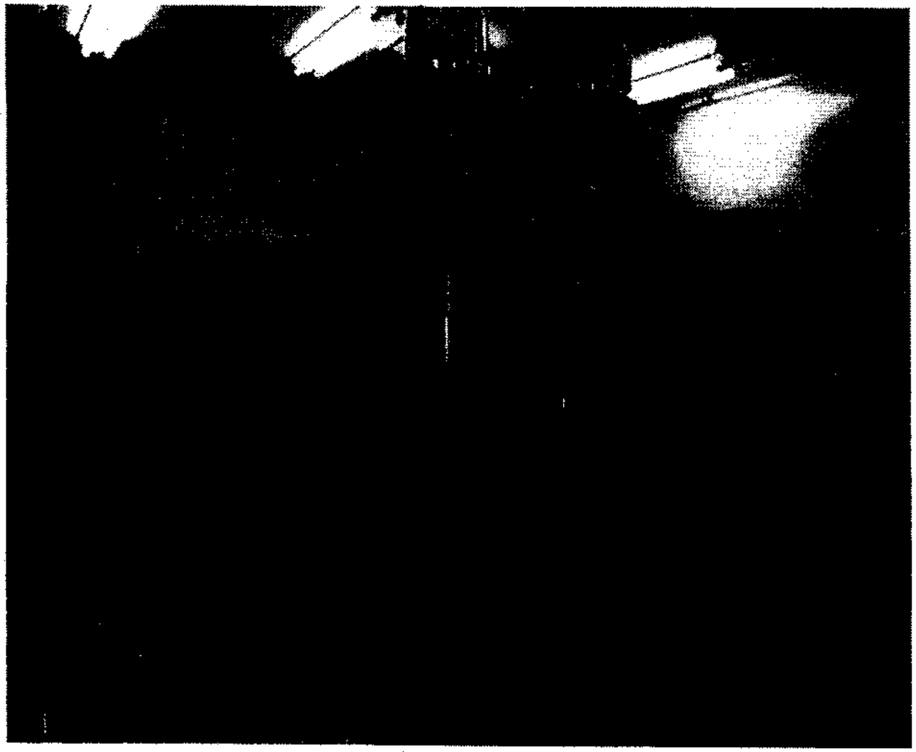
Gray-scale occulting spot fabrication method

- Electron-beam exposure
  - JEOL 9300FS at JPL (50 or 100 kV acceleration voltage)
  - Electrons scatter and slow as they penetrate the glass, resulting in graying around primary spot ("proximity effect") and non-uniform graying as a function of depth (not yet characterized, experiment in progress)



E-Beam Lithography at JPL

JEOL JBX-9300FS



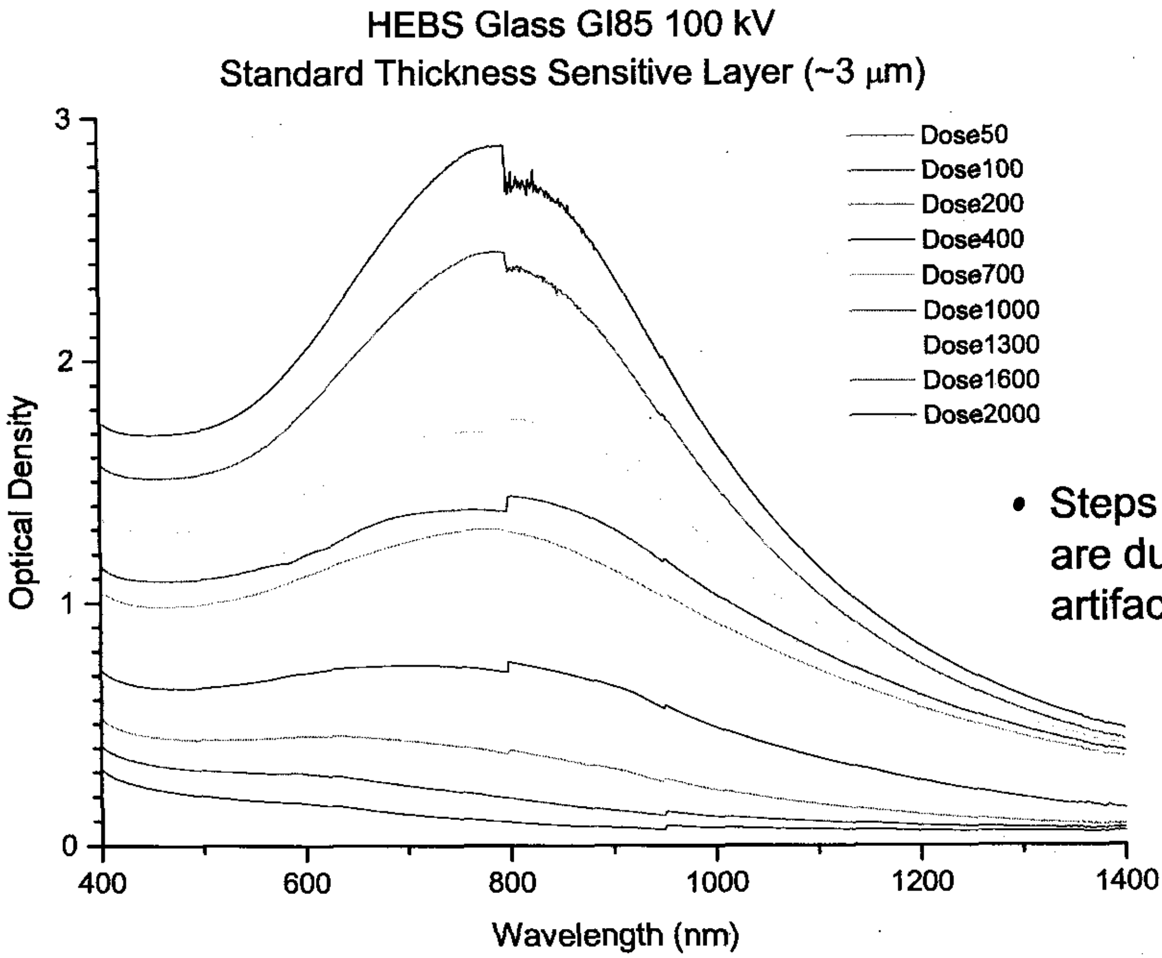
State-of-the-Art Electron-Beam Lithography System

Parameter	***JEOL JBX-9300FS***	
Voltage	100 kV	50 kV
Minimum Spot Size	4 nm	7 nm
Beam Current for: 100 nm spot	175 nA	125 nA
10 nm spot	10 nA	4 nA
Field Size	500 µm	1000 µm
Pattern Generator Speed	25 MHz	
Field Stitching Accuracy	20 nm	
Write Area	9 in sq	
Wafer Size	12 in dia	
Writing Grid	1 nm	2 nm
Electron Source	ZrO/W Field Emission Gun	
Deflection System	Dual Deflector Low-speed 19-bit DAC High-speed 12-bit DAC Dynamic focus Dynamic astigmatism	
Fine-Pitch Control	±5%	
Height Control	White-light measurement Auto-correction direct-write, ±0.2 mm Manual via Jobdeck, ±2 mm	
Cabling	Ethernet	
Computer Control	Local Smarts - 3 Internal DEC Alpha CPUs	

HEBS Glass Calibration

Optical density as function of wavelength and dose

- 3 x 3 mm areas exposed and measured with a spectrophotometer
- Peak OD is near 800 nm for 'GI85' glass
- 100 kV electrons go through 3 μm sensitive layer – much more OD possible with a thicker layer

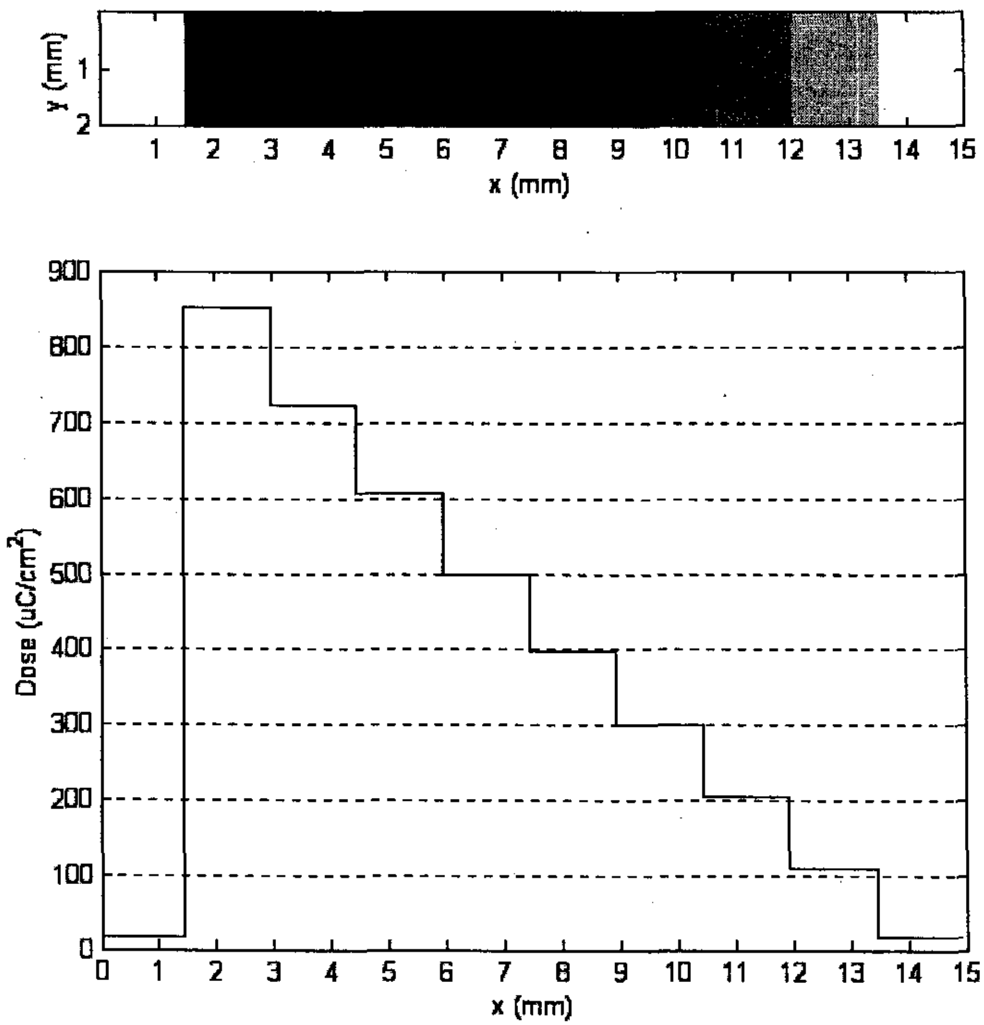


- Steps in OD at 800 nm are due to instrument artifacts (grating changes)

HEBS Glass Calibration

Optical density vs. dose calibration

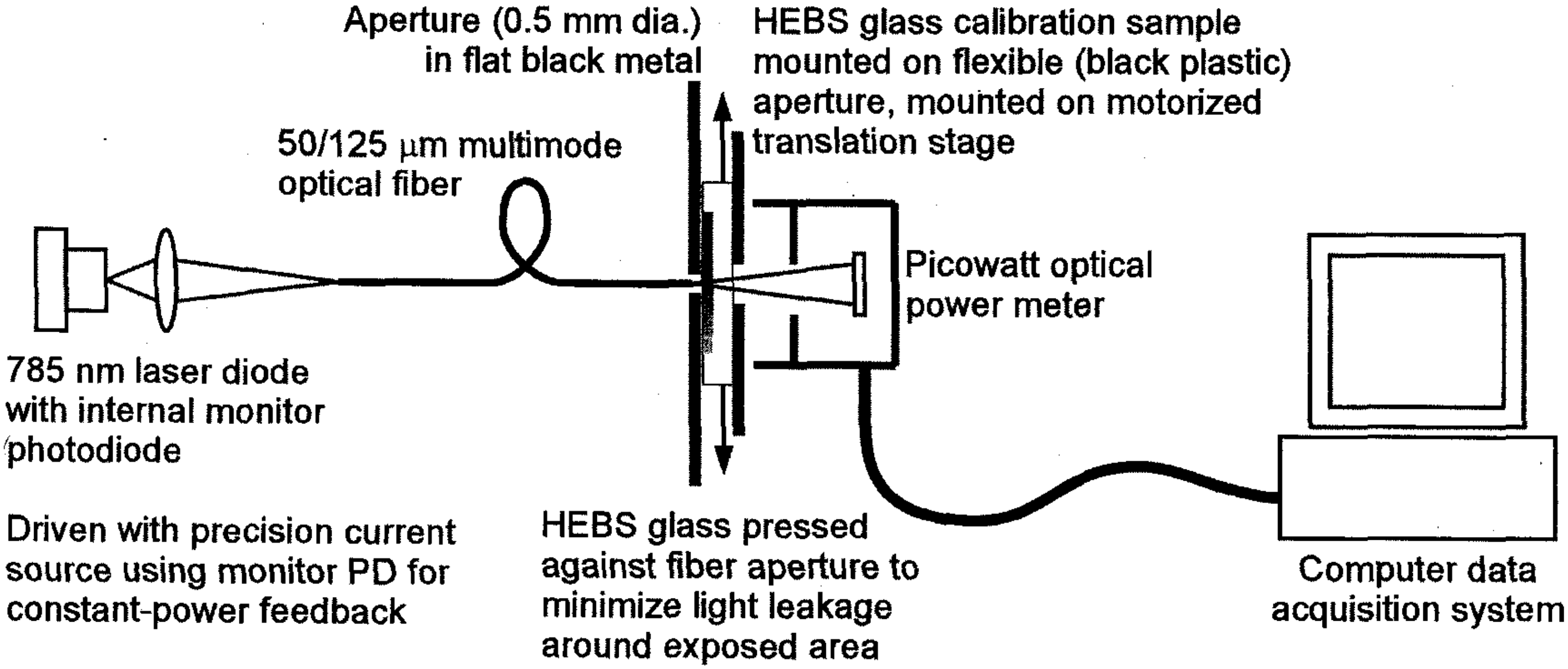
- OD measurements using laser near peak wavelength (785 nm)
- Calibration pattern with constant-dose steps



HEBS Glass Calibration

Optical density vs. dose calibration (cont.)

- Optical density measurement setup

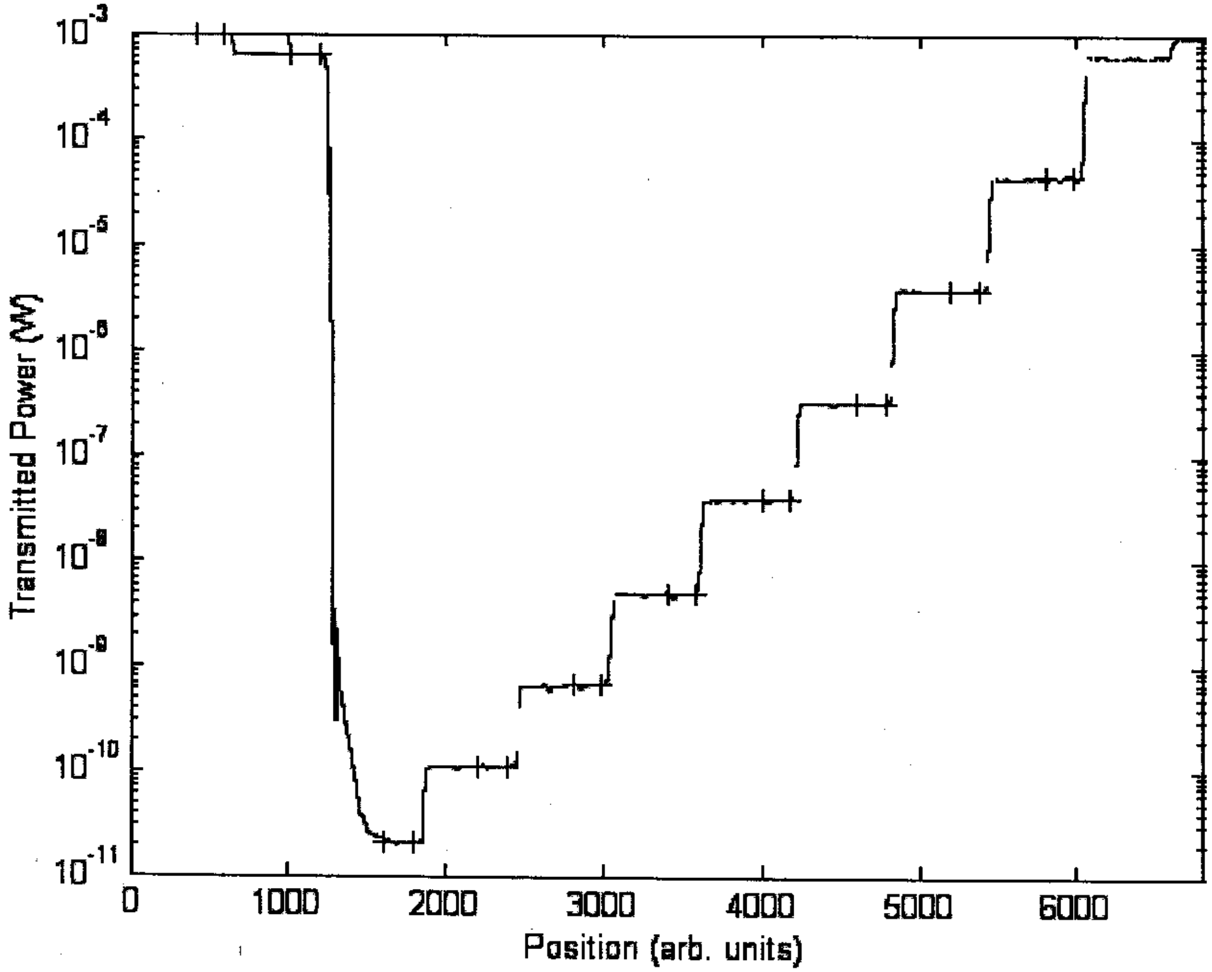


- Optical fiber is convenient for light delivery and provides well-defined source, but end-face reflection and large divergence reduces spatial resolution and maximum OD of setup – will eliminate in future

HEBS Glass Calibration

Optical density vs. dose calibration (cont.)

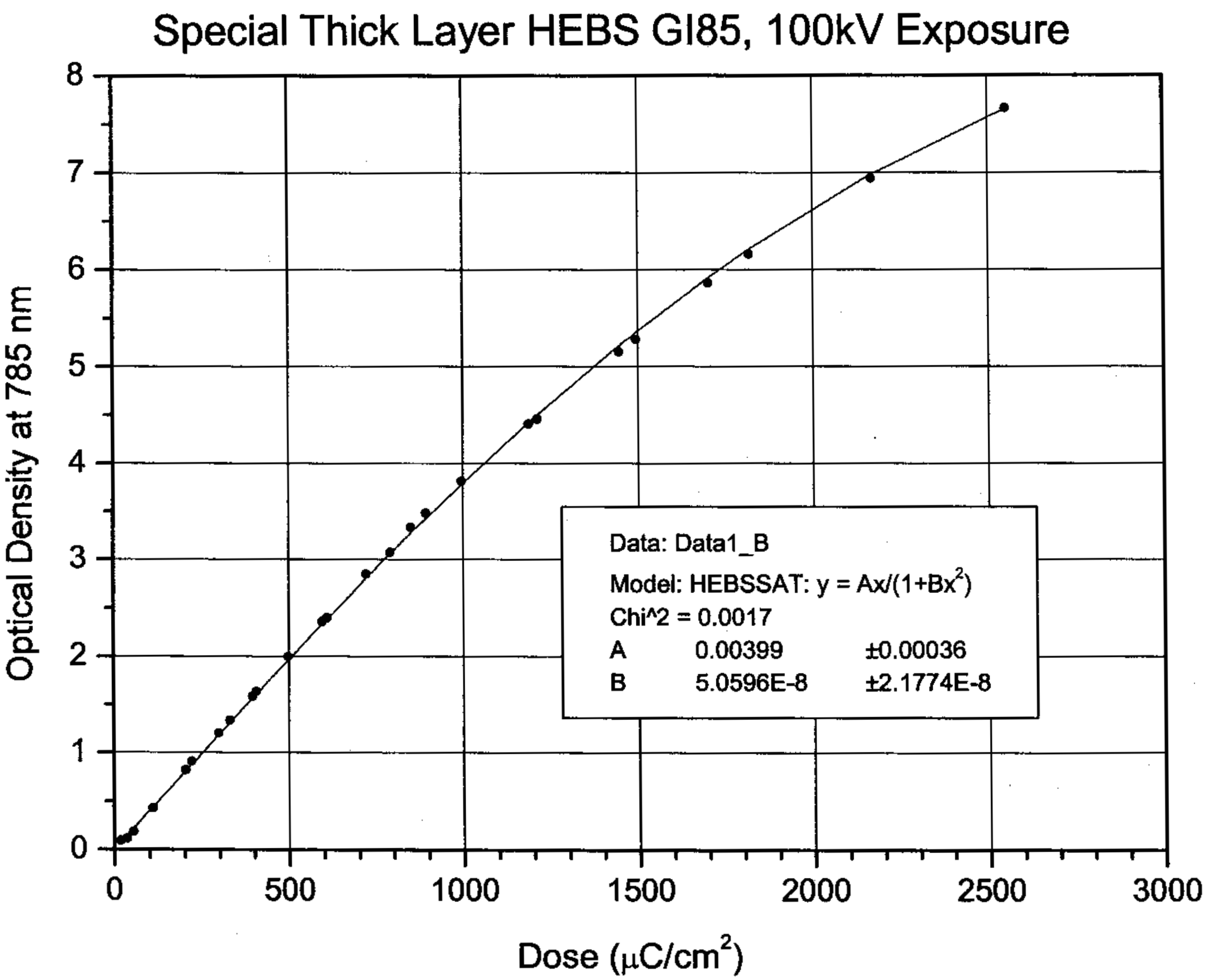
- Experimental data from HEBS glass scan



HEBS Glass Calibration

Optical density vs. dose calibration (cont.)

- OD 8 at 785 nm will be possible with a dose of ~3000 $\mu C/cm^2$
- Data fit with saturating function to use for converting spot OD functions to dose



Proximity effect characterization

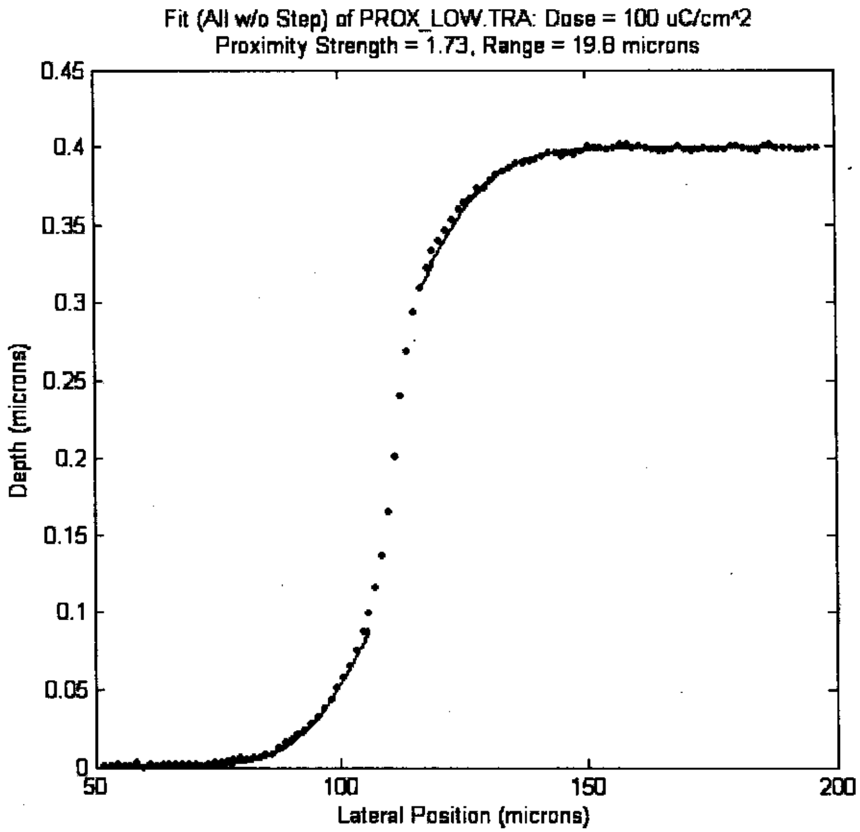
- Total dose is convolution of primary dose pattern and point spread function

$$Dose_{\text{total}}(\mathbf{r}) = Dose_{\text{primary}}(\mathbf{r}) \otimes PSF(\mathbf{r})$$

$$PSF(\mathbf{r}) = \delta(\mathbf{r}) + \frac{\eta}{\pi\alpha^2}\exp(-r^2/\alpha^2)$$

$$\int_{\infty} PSF(\mathbf{r})d\mathbf{r} = 1+\eta$$

η is "strength", α is "range"



Fit of Optical Density Scan at Edge of Uniform Dose Exposure

- Analytical convolution of PSF with primary dose step function

$$Dose_{\text{total}}(x) = Dose_{\substack{\text{primary}\\ \text{constant}}}\left\{\text{step}(x - x_{\text{step}}) + \frac{\eta}{2}\left[1+\text{erf}\left(\frac{x - x_{\text{step}}}{\alpha}\right)\right]\right\}$$

- From dose, optical density

$OD(x) = f\{Dose_{\text{total}}(x)\}$, where f is OD vs. $Dose$ calibration curve

Proximity effect compensation

Given a desired intensity transmittance function $T(\mathbf{r})$

1. Calculate optical density function $OD(\mathbf{r}) = -\log[T(\mathbf{r})]$
2. Use OD vs. dose calibration curve (and proximity strength) to determine desired *total* dose function
3. Deconvolve the proximity effect out of the total dose function to yield the *primary* dose function

$$D_{\text{primary}}(\mathbf{r}) = F.T.^{-1}\left\{\frac{F.T.\{D_{\text{total}}(\mathbf{r})\}}{F.T.\{PSF(\mathbf{r})\}}\right\}$$

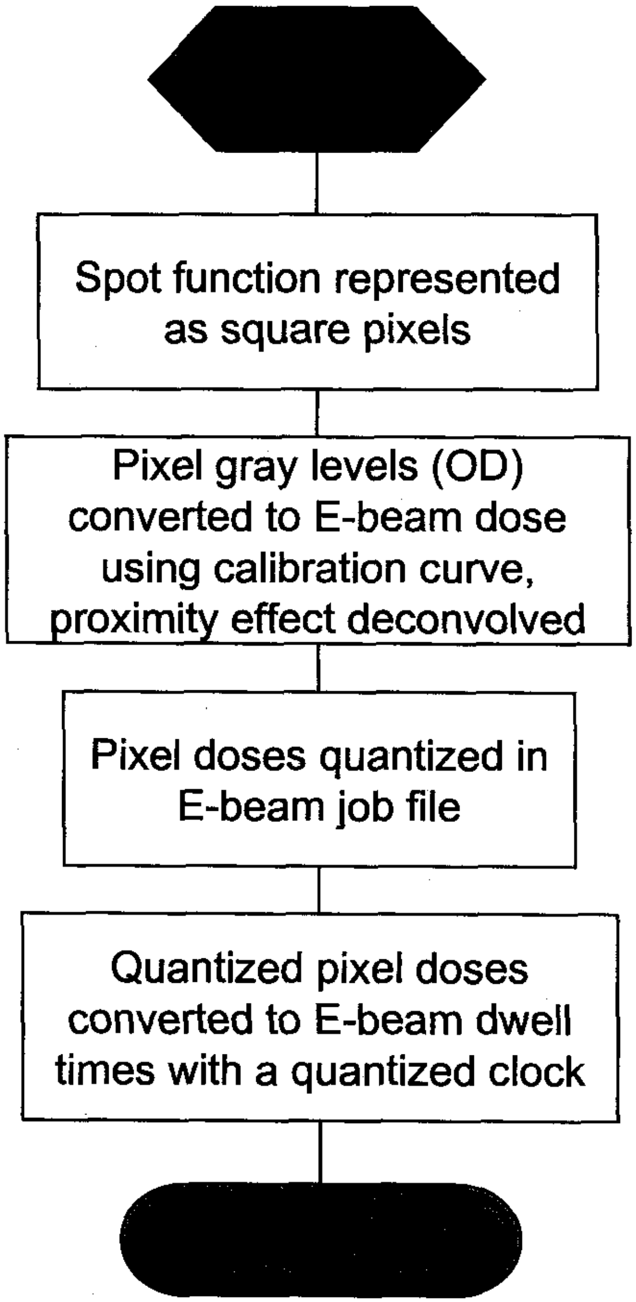
- Analytical Fourier transform of PSF is used for efficiency
- Zero padding used to prevent periodic effects of FFT

Electron-Beam Exposure Optimization

E-beam pattern preparation

- Optical density of spot function is represented as square pixels with sizes less than wavelength (0.1 to 0.5 μm)
- Pixel optical densities are converted to E-beam doses ($\mu C/cm^2$) using OD vs. dose calibration curve and proximity effect is deconvolved from dose pattern
- Doses are quantized to multiples of 0.001 x 'base dose' in job file (typical dose resolution of 0.1 $\mu C/cm^2$)
- Doses are converted to E-beam dwell times with a minimum clock resolution of 0.2 ns

- Quantization effects can be minimized by proper selection of job file parameters and background dose



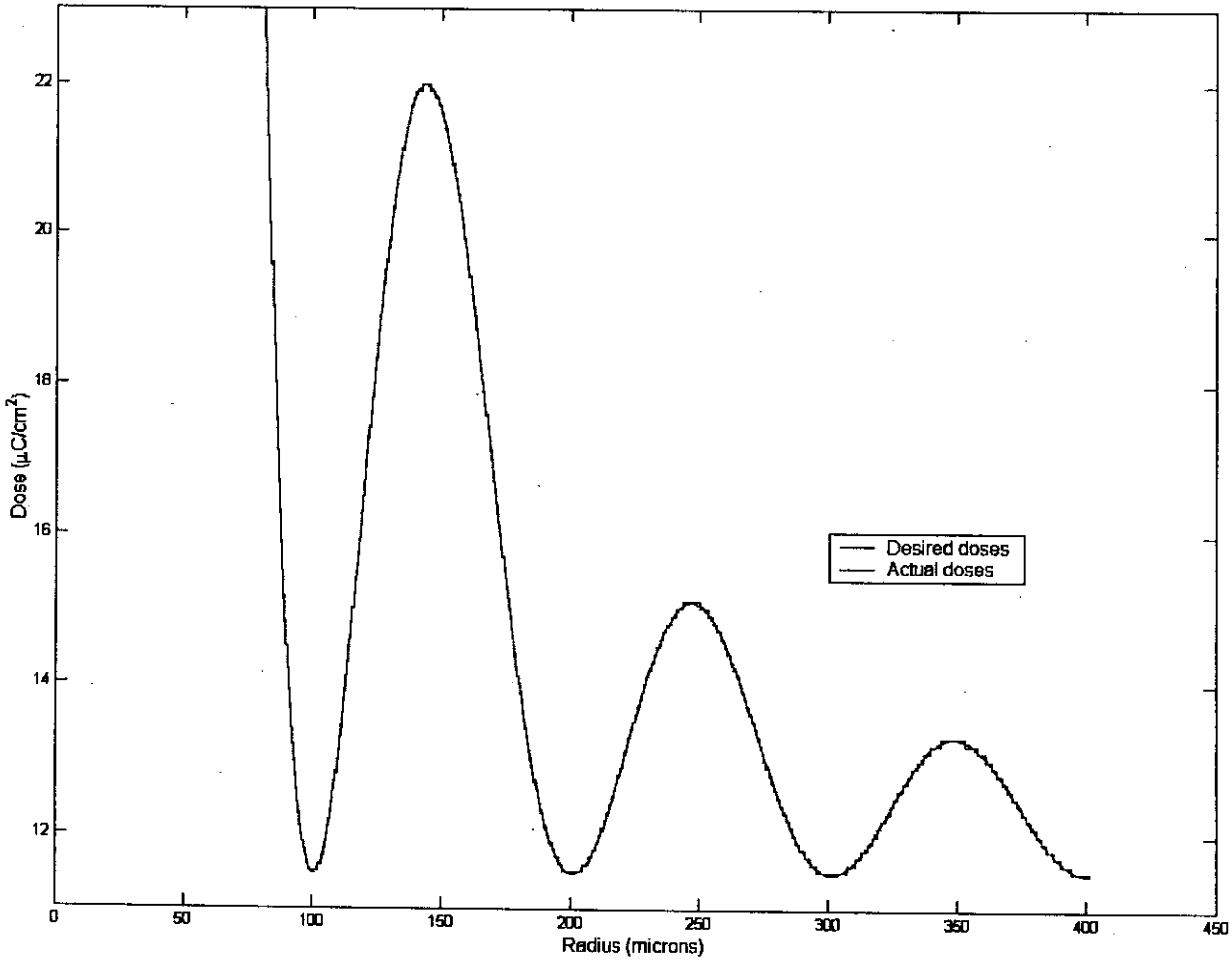
Electron-Beam Exposure Optimization

Exposure optimization example

- Job file quantization
  - Using a 'base dose' of 100 $\mu C/cm^2$, available doses (job file limited) are 0.1, 0.2, 0.3 … 3299.8, 3299.9, 3300 $\mu C/cm^2$ (can achieve desired maximum OD > 8)
  - Using a background dose of ~10 $\mu C/cm^2$
    - At low doses (max T, edges), functional accuracy is 0.1/10 = 0.01
    - At high doses (min T, center), functional accuracy is 0.1/3000 = 3.3×10^{-5}
- Dwell time clock quantization (minimum clock resolution = 0.2 ns)
  - At center of spot, dose = ~3000 $\mu C/cm^2$, dwell time = 12000 ns, quantization error = 0.2/12000 = 1.7×10^{-5} (negligible)
  - At outer radius of spot, dose = ~10 $\mu C/cm^2$, dwell time = 40 ns, quantization error = 0.2/40 = 0.005 (less than job file limitation)

Exposure optimization example (cont.)

- Airy rings of $sinc^2$ pattern are the only place dose quantization errors are even visible (note that maximum dose is ~3000 μC/cm² and this plot is in the 11-23 μC/cm² range)



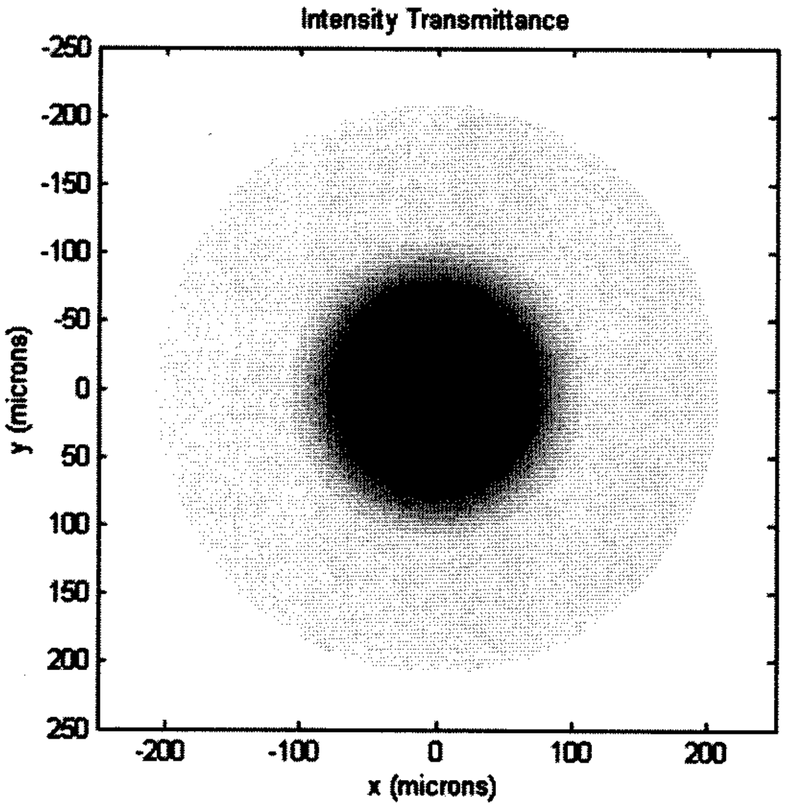
Fabricated Occulting Spot Results

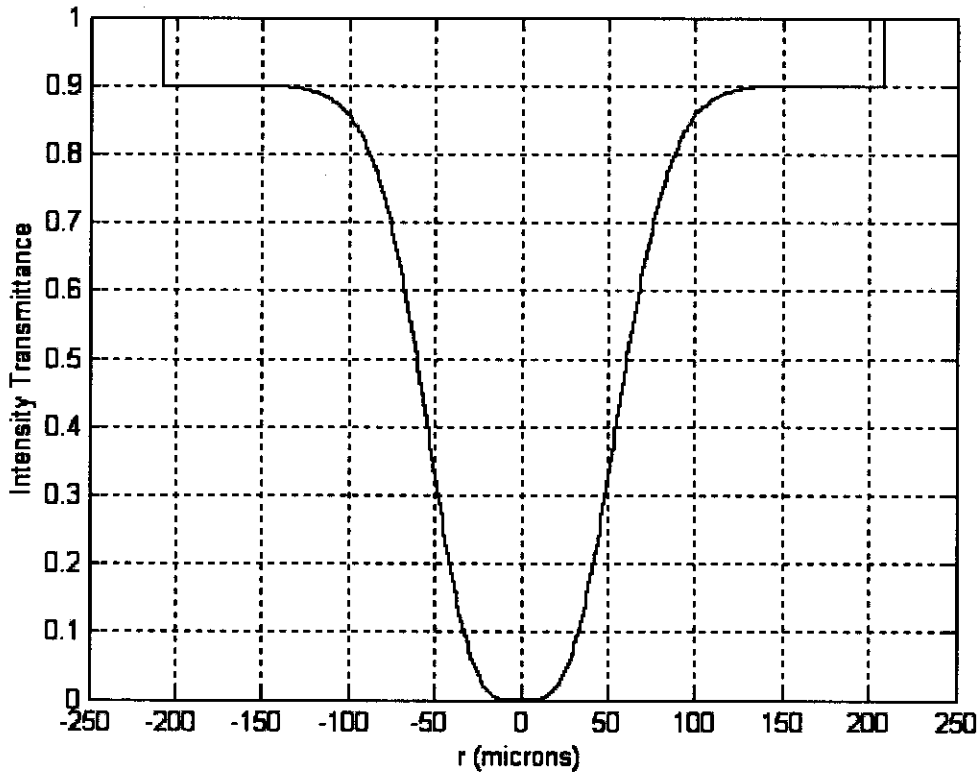
Occulting spot designs

1. Circular Gaussian:

$$T(r) = T_{\max}\left[1 - \alpha e^{-(r/\sigma)^2}\right]^2$$

$$T_{\max} = 0.9,\ \ \alpha = 1 \text{ (no OD limit)},\ \ \sigma = 52.0\ \mu\text{m},\ \ r_{\max} = 4\times 52 = 208\ \mu\text{m}$$



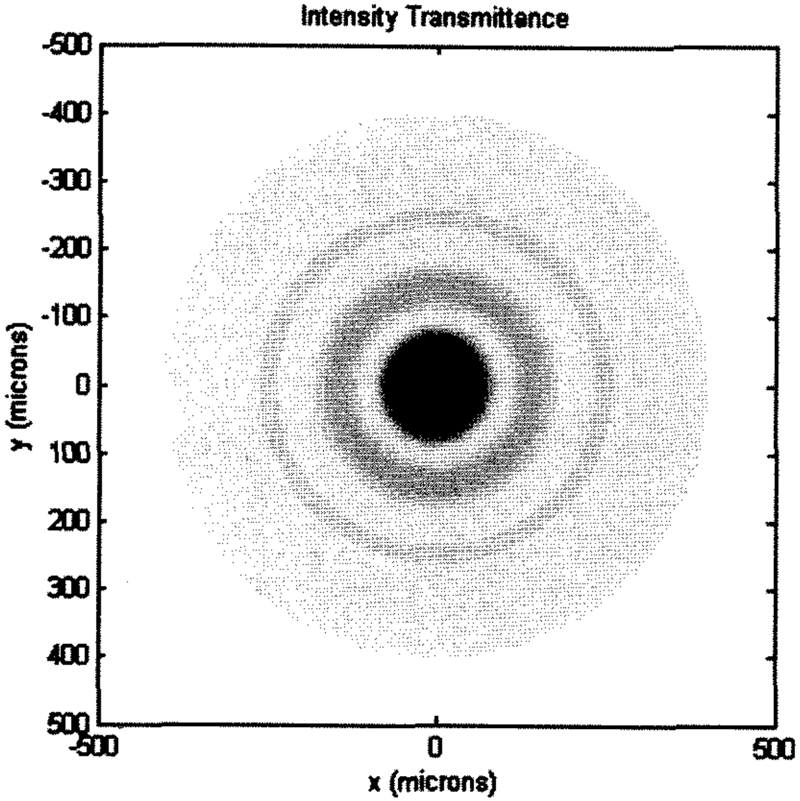


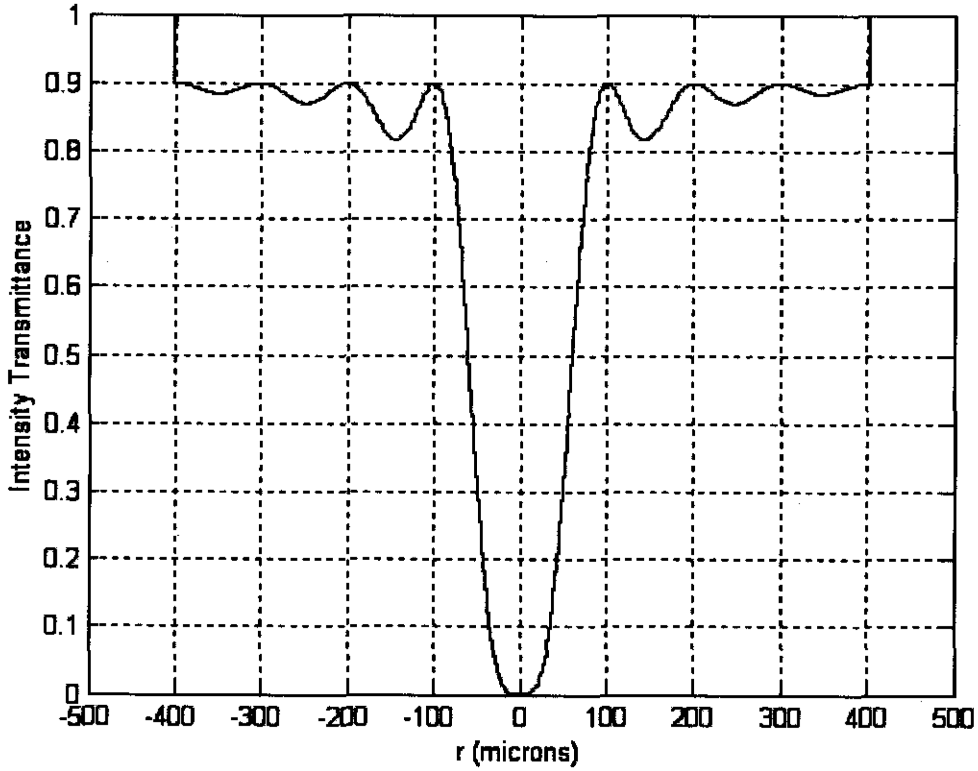
Occulting spot designs (cont.)

2. Circular sinc^2:

$$T(r) = T_{\max}\left[1-\alpha\left[\frac{\sin(\pi r/w)}{\pi r/w}\right]^2\right]^2$$

$T_{\max} = 0.9$, $\alpha = 1$ (no OD limit), $w = 100.5\ \mu\text{m}$, $r_{\max} = 4\times 100.5 = 402.0\ \mu\text{m}$





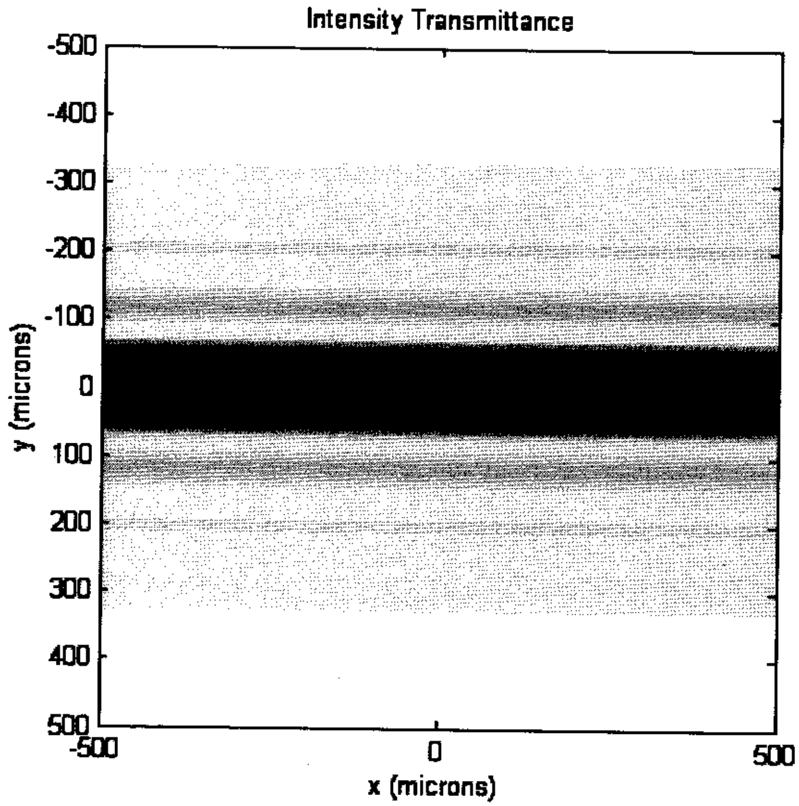
Fabricated Occulting Spot Results

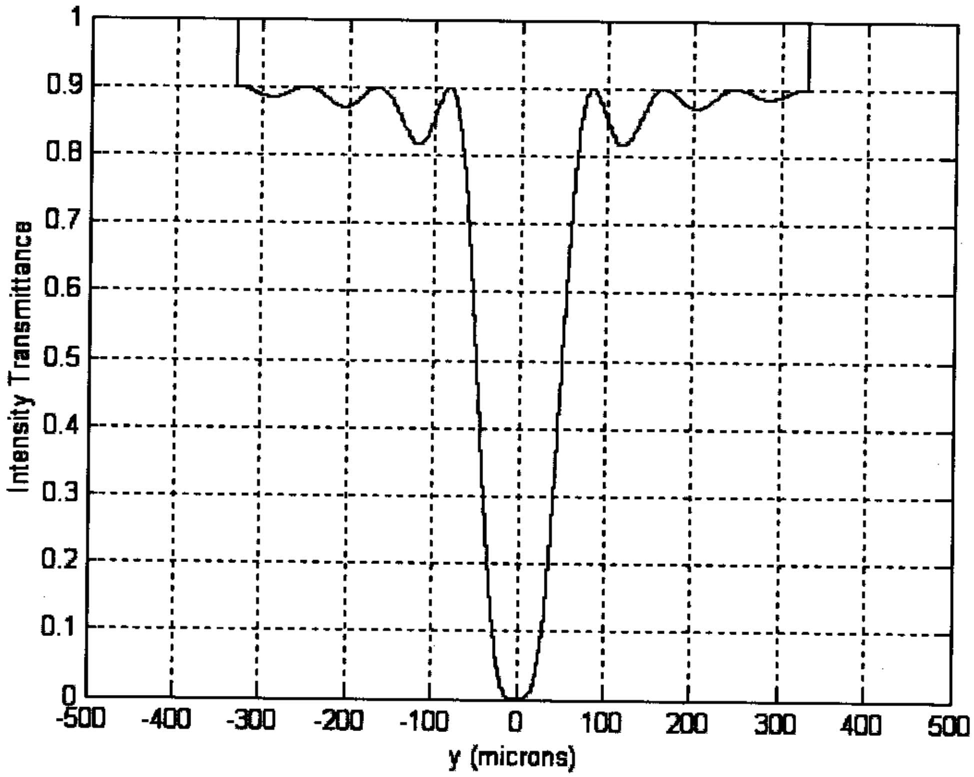
Occulting spot designs (cont.)

3. Linear sinc²:

$$T(x) = T_{\max}\left[1 - \alpha\left[\frac{\sin(\pi x / w)}{\pi x / w}\right]^2\right]^2$$

$$T_{\max} = 0.9,\ \alpha = 1 \text{ (no OD limit)},\ w = 82.9\ \mu\text{m},\ x_{\max} = \pm 4 \times 82.9 = \pm 331.6\ \mu\text{m}$$

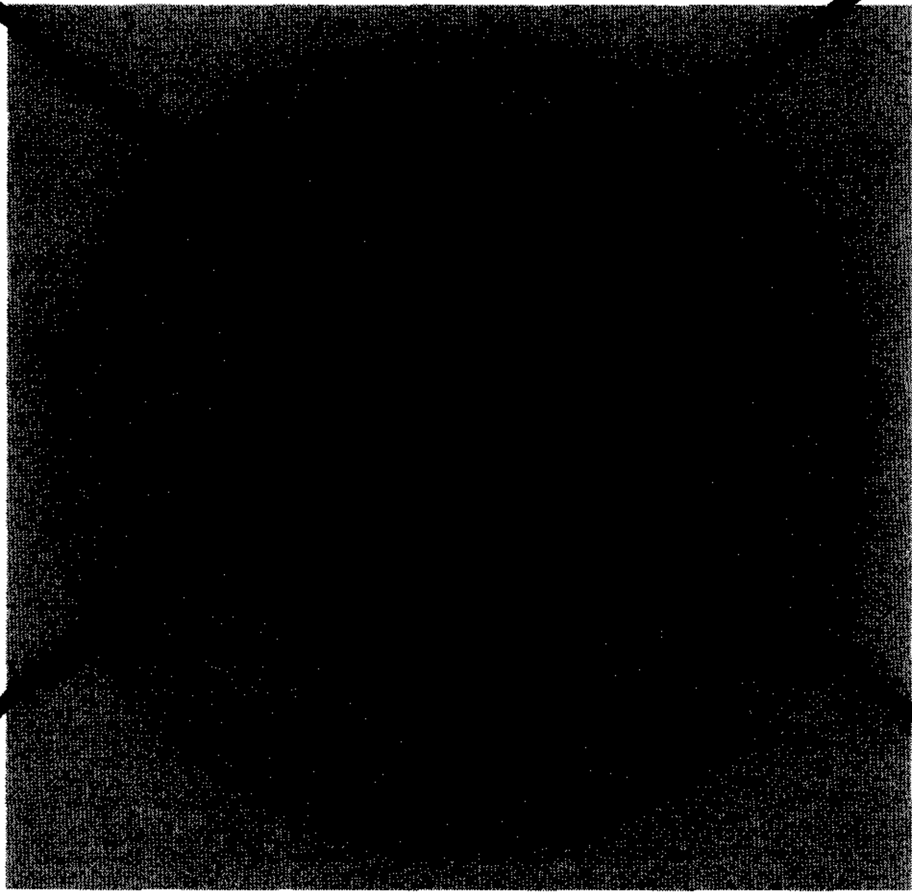




Fabricated Occulting Spot Results

Images of fabricated spots (not corrected for proximity effect)

1. Circular Gaussian

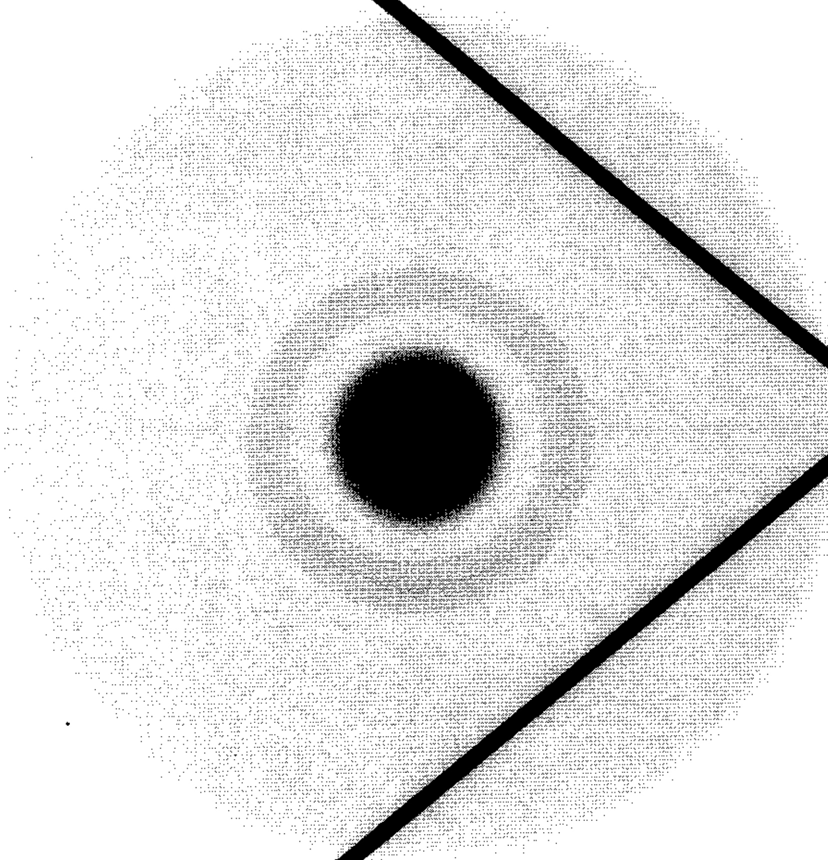


Raw image

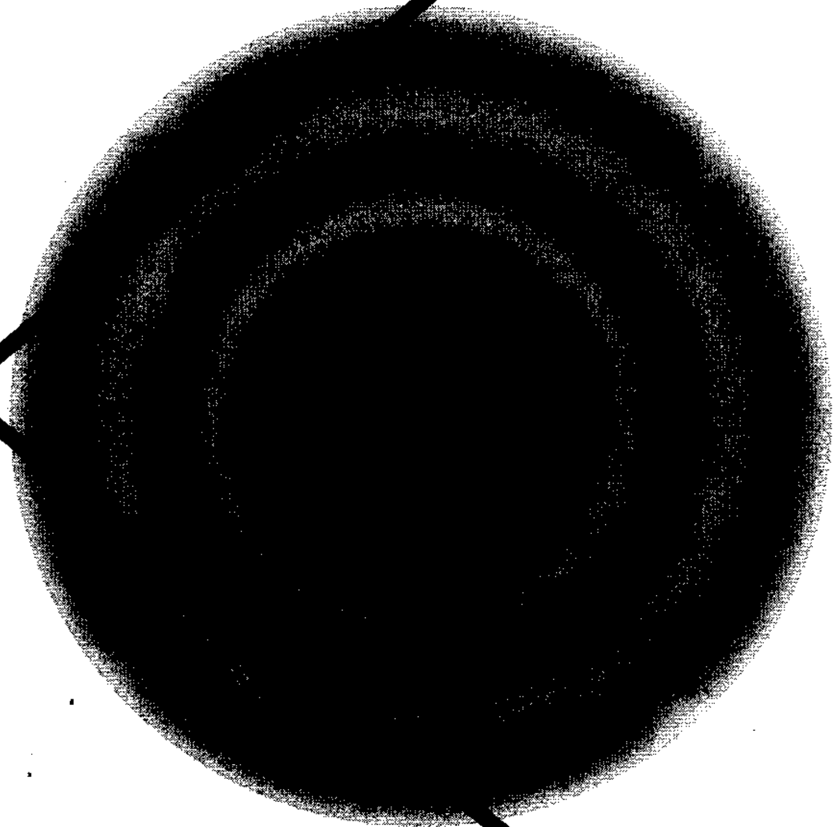
Fabricated Occulting Spot Results

Images of fabricated spots (cont.)

2. Circular $sinc^2$



Transmittance Image
(Spot image / clear glass)

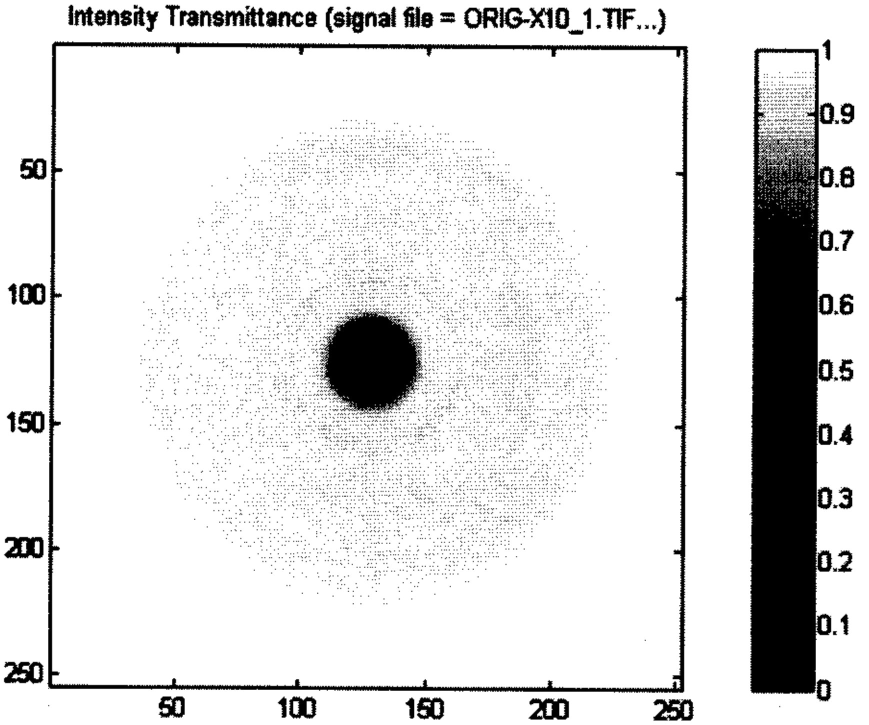


Hard colormap stretch shows
E-beam exposure errors – likely due
to charging of the the HEBS glass

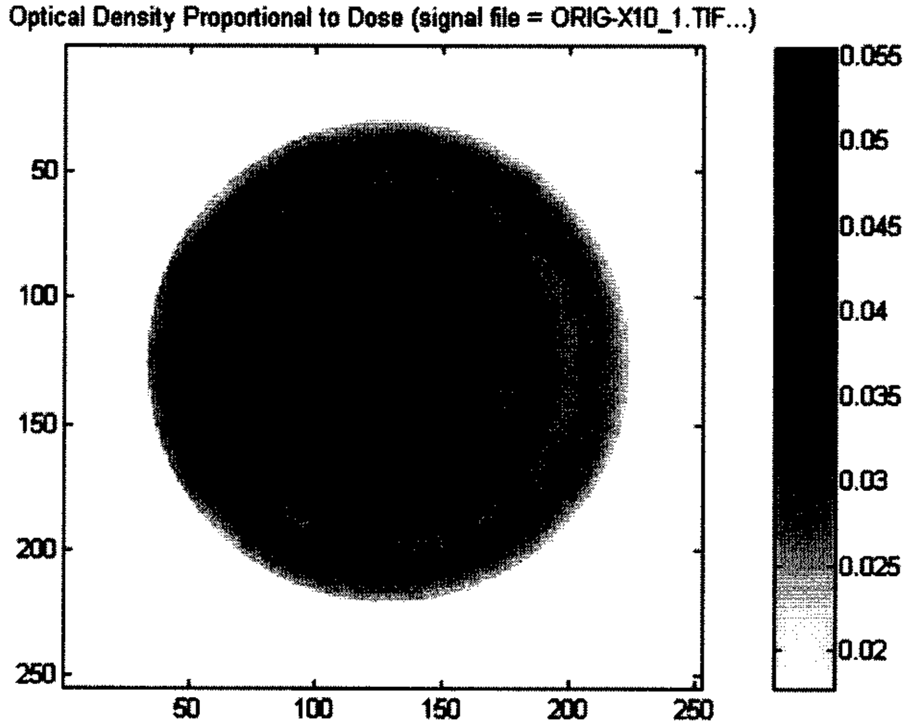
Fabricated Occulting Spot Results

Images of fabricated spots (cont.)

2A. Circular sinc^2 – Exposed 10 times with 1/10 dose to correct non-uniformity



Transmittance Image
(Spot image / clear glass)

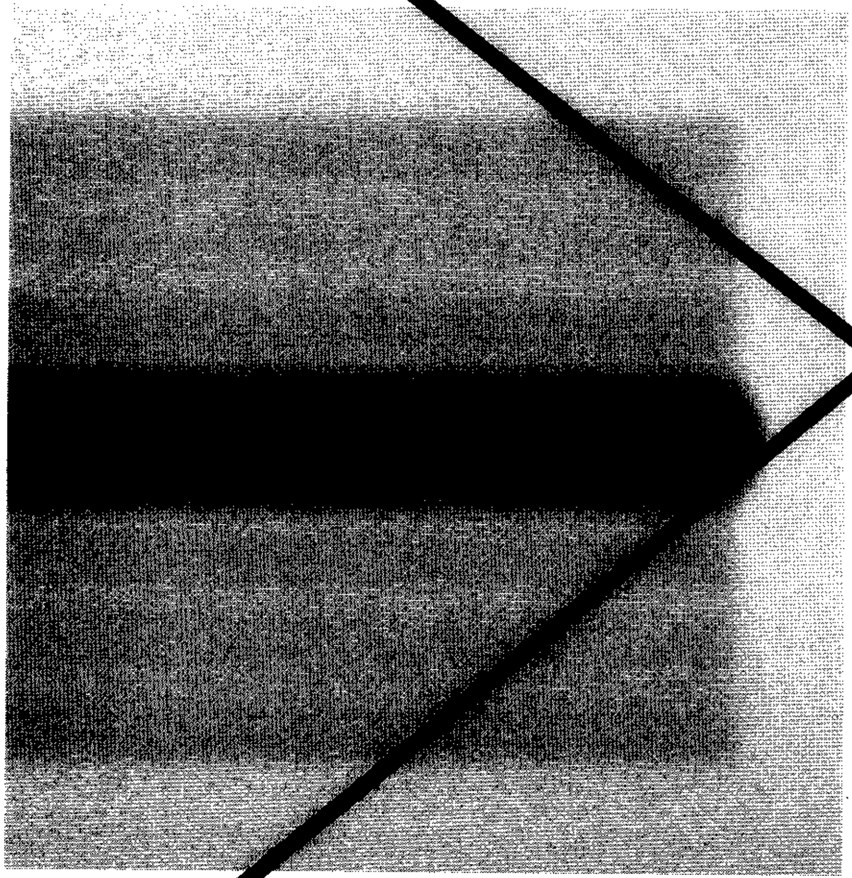


Non-uniformity is corrected
(image is poor due to uncooled camera)

Fabricated Occulting Spot Results

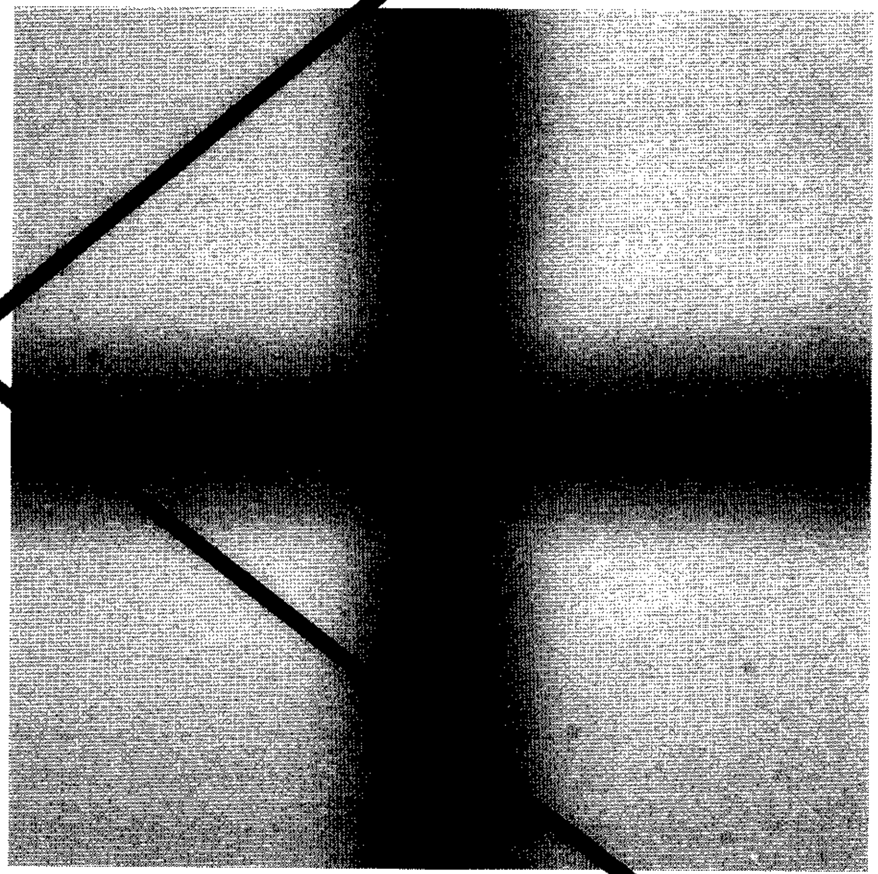
Images of fabricated spots (cont.)

3. Linear $sinc^2$



Raw image

4. Alignment cross (10 μm wide)

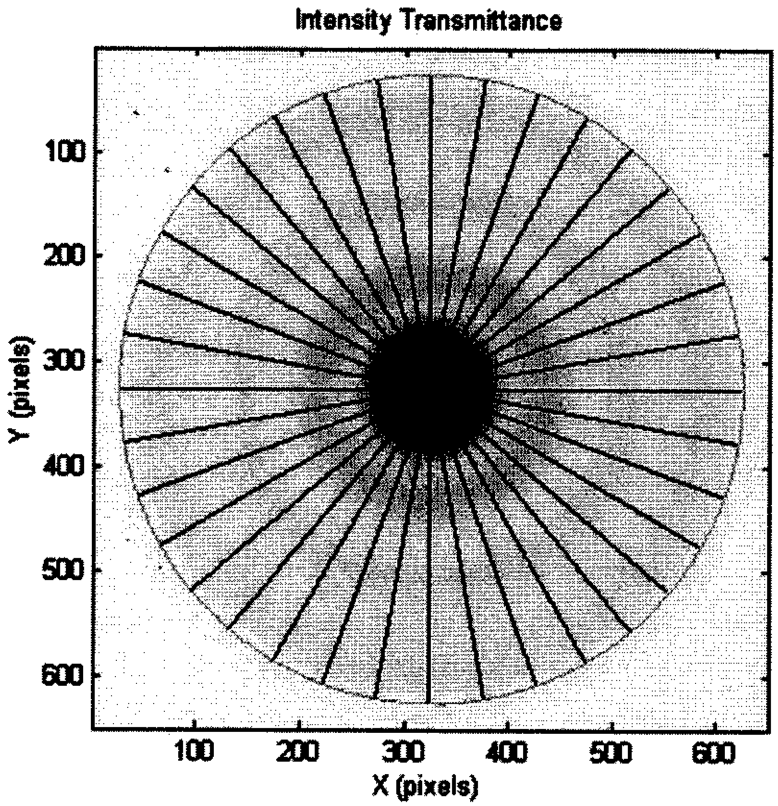


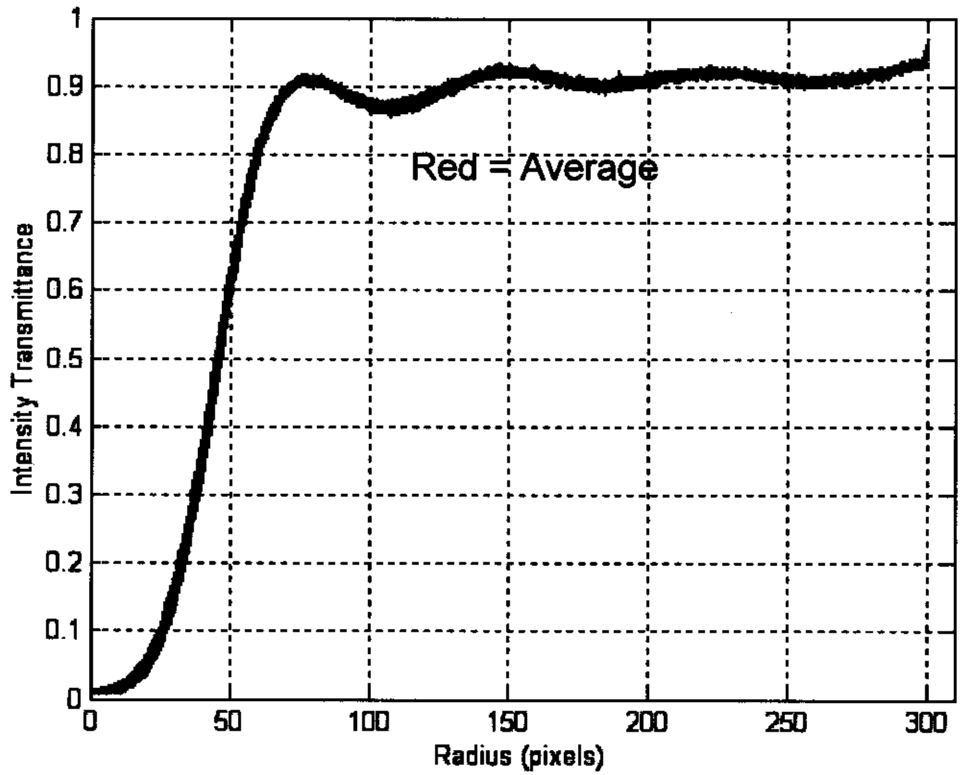
Raw image

Fabricated Occulting Spot Results

Comparison to design transmittance

- Circular $sinc^2$ – average transmittance along radial slices





Fabricated Occulting Spot Results

Comparison to design transmittance (cont.)

- Circular $sinc^2$
  - Comparison of radial slice average transmittance to design function
  - Errors can be explained by proximity effect and measurement error