Diffractive Optical Elements

Lens Design OPTI 517

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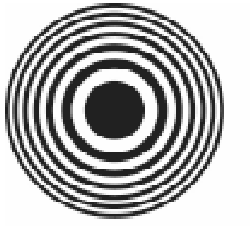
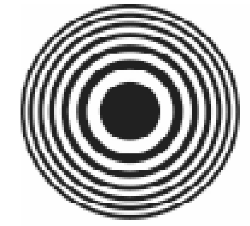


Diffractive Lenses



- What they are
- How they work
- Zone spacing and blaze profile roles
- First order properties
- Dispersion
- Two point construction model
- Phase model
- Sweatt model
- Efficiency
- Diffractive landscape lens

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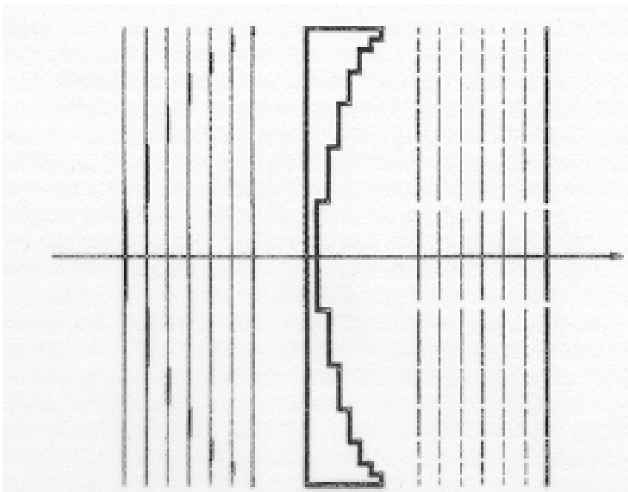
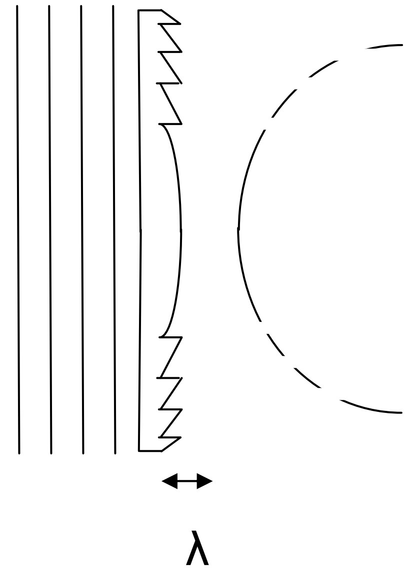
Terminology

- Diffractive optical element: generic term
- Fresnel lens: Scale of zones and lack of organized phasing
- Kinoform: Phased Fresnel lens. Phase modulation from surface relief
- Holographic optical element: Produced by interfering two or more beams
- Binary optics: Made by staircases that approximate the ideal surface relief
- Fresnel zone plate: A particular pattern that produces amplitude modulation.
- Hybrid lens: combined refractive and diffractive power
- Computer generated hologram: A hologram produced by calculations in a computer

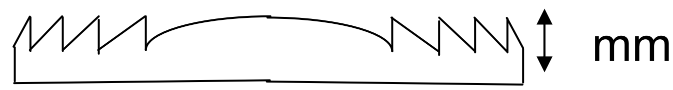
The work of a diffractive optical element

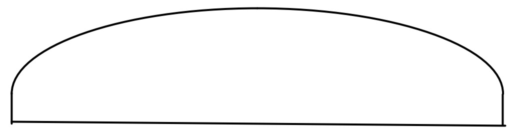


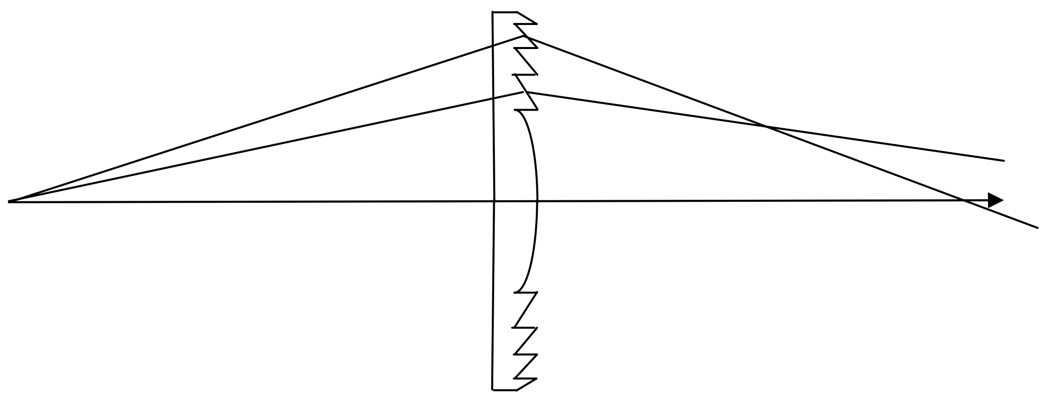


Organized rearrangement of the wavefront

Fresnel Lens







A Fresnel lens reduces the amount of bulk glass.
Scale of zones is large and the wavefront segments are not rearranged to re-create a spherical wavefront.
The ring-zone segments is not properly organized.

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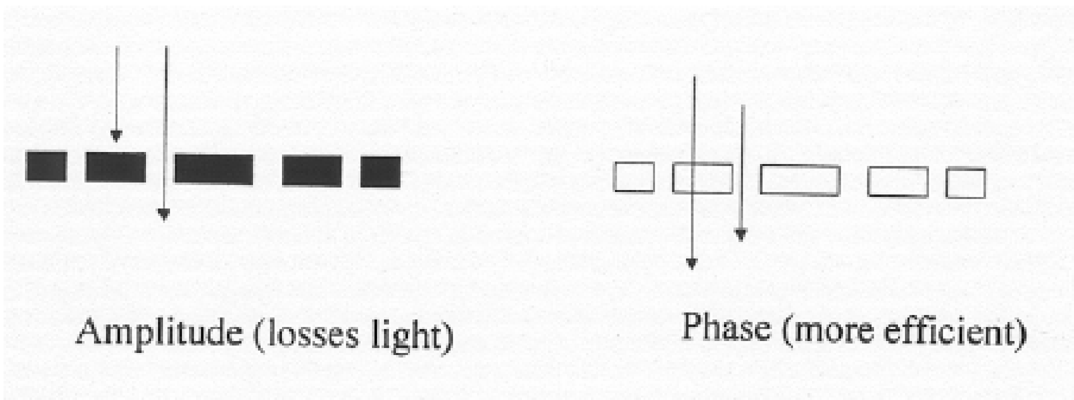
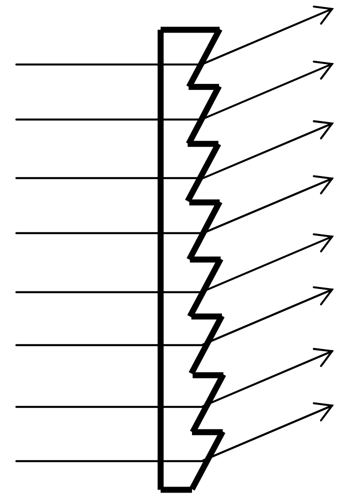
Two contexts for DOE: amplitude and phase

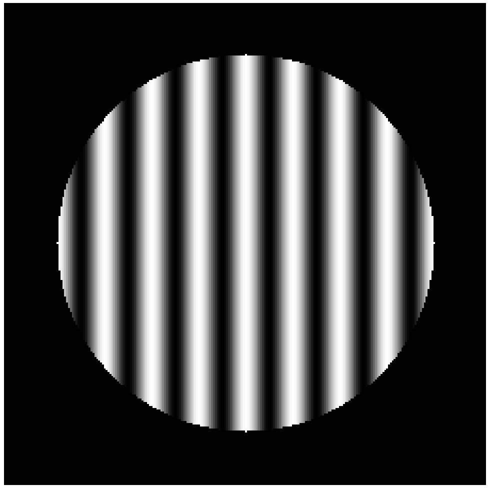


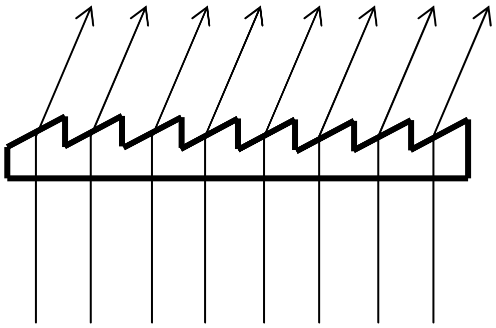


- Blaze determines amplitude of diffracted orders
- Geometry of zone boundary determines wavefront shape (phase)

- The wavefront deformation introduced by a DOE is equal to the wavefront deformation represented by the DOE when it is thought of as an interferogram

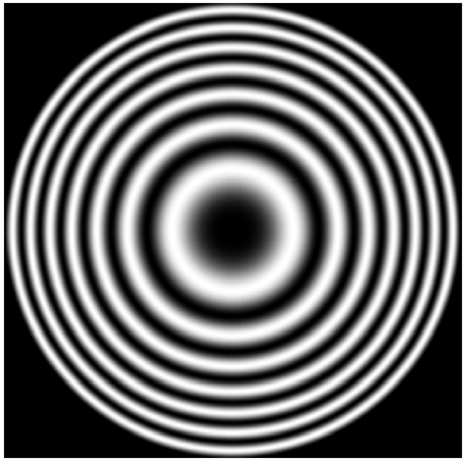
Example

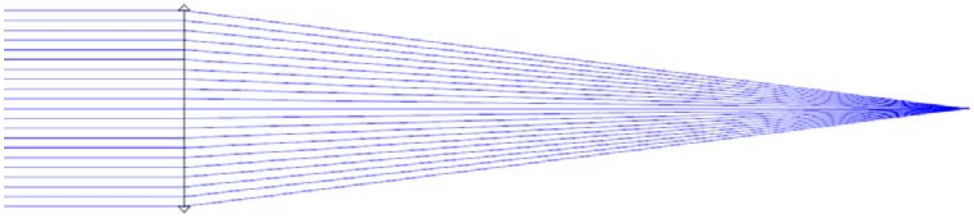


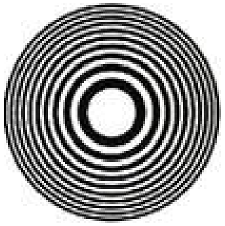


- Straight fringes represent tilt and so the beam is deviated

Example

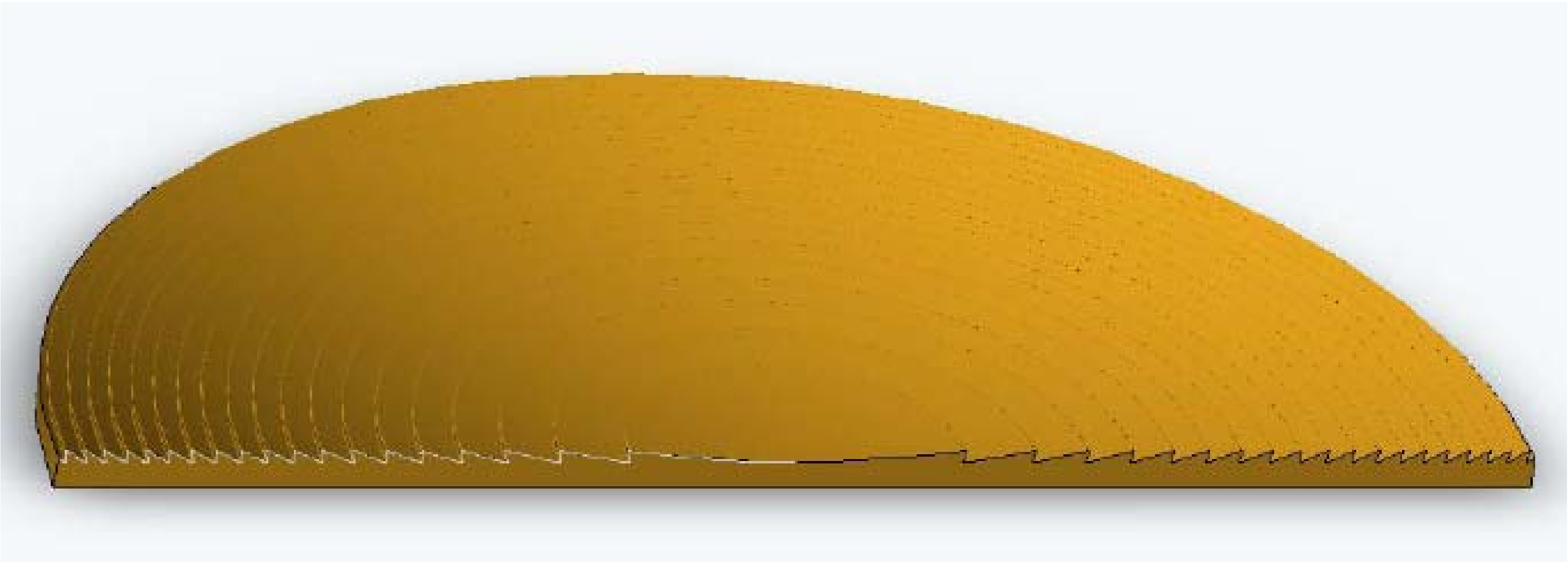






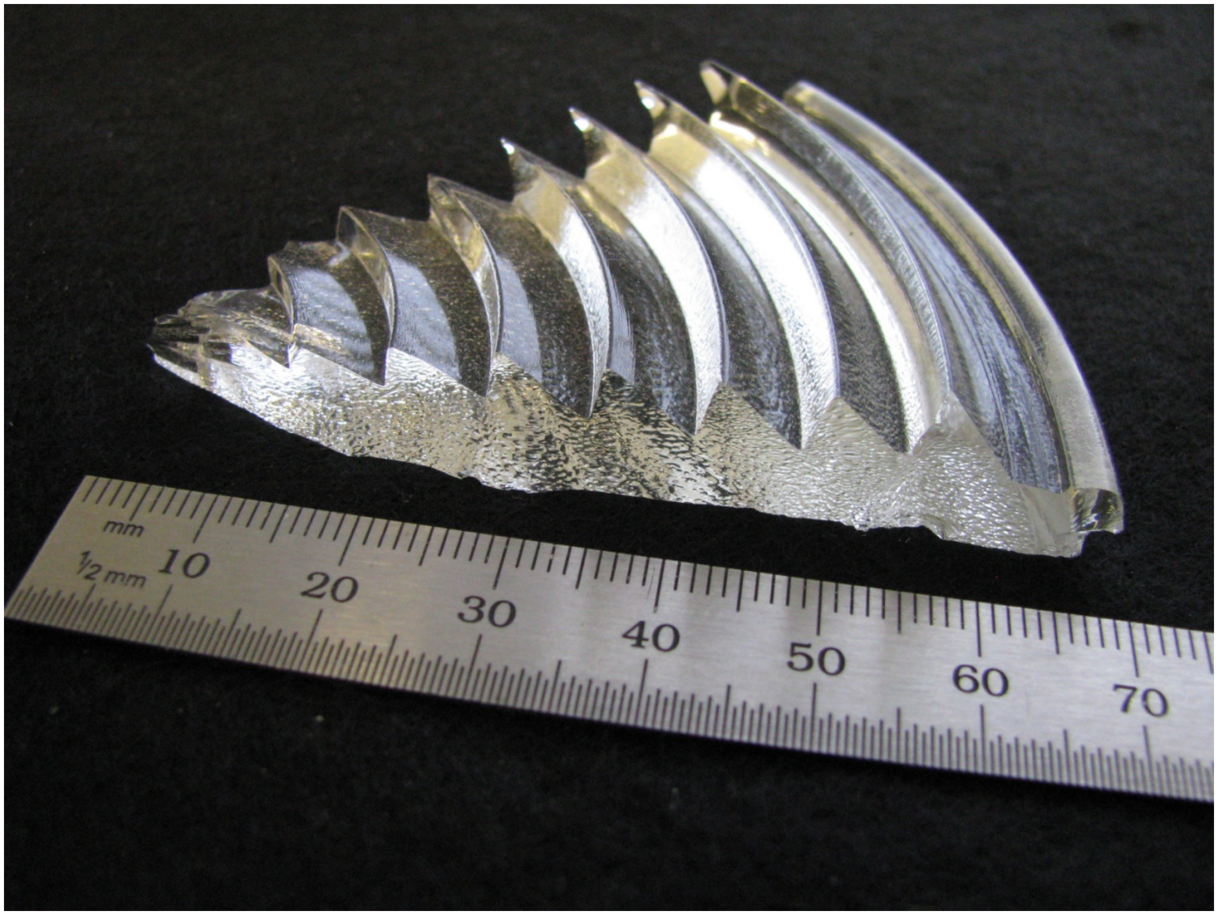
- Circular fringes represent defocus and so a DOE with these zone boundaries will introduce optical power
- Depending on the spacing, spherical aberration can also be introduced

An infrared DOE

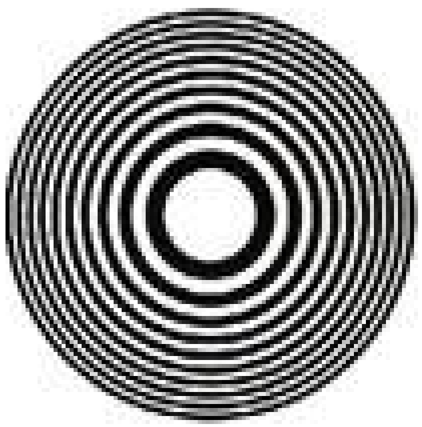


From Michael Morris

A Fresnel lens cut-away



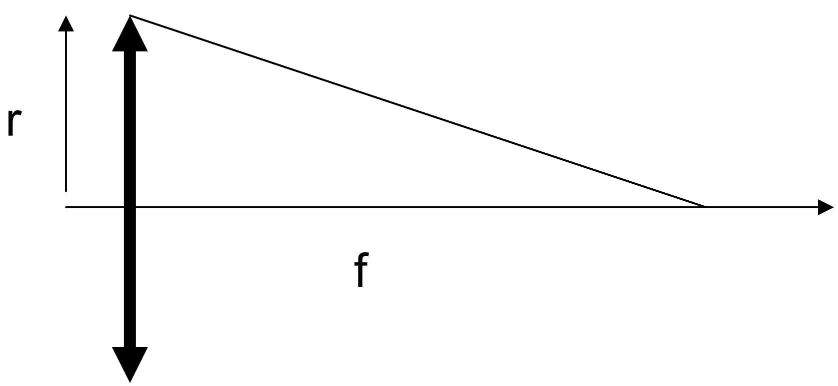
First-order properties



$$\sqrt{f^2 + r_n^2} = f + n\lambda$$

$$f^2 + r_n^2 = f^2 + 2nf\lambda + n^2\lambda^2$$

$$r_n \cong \sqrt{2nf\lambda}$$



Given a focal length the zone
 boundaries are defined.
The optical path difference
Between zones is
one wavelength

Paraxial diffractive lens definition

$$r_n = \sqrt{2nf\lambda}$$

Design of a wide field diffractive landscape lens

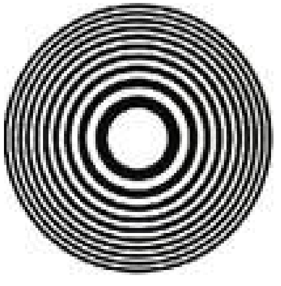
Dale A. Buralli and G. Michael Morris

Zone Spacing

$$r_n^2 \cong 2nf\lambda$$

$$r_n^2 - r_{n-1}^2 = \left(r_n + r_{n-1}\right)\left(r_n - r_{n-1}\right) \cong 2r_n dr = 2f\lambda$$

$$Spacing = dr \cong \frac{f}{2r_n} 2\lambda \cong F/\#_{micrometers}$$



Focal length for a given spacing

$$f = \frac{r_n \cdot dr}{\lambda_{construction}} \times \frac{\lambda_{construction}}{\lambda_{reconstruction}} = f_0 \times \frac{\lambda_{construction}}{\lambda_{reconstruction}}$$

Designed for $\lambda_{construction}$

Used at $\lambda_{reconstruction}$

Abbe's number for a refractive lens

$$\phi_{refractive} = \frac{(n-1)}{R}$$

$$\frac{\partial \phi}{\partial \lambda} = \frac{1}{R}\frac{\partial n}{\partial \lambda}$$

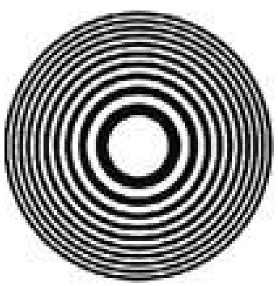
$$\partial \phi = \frac{1}{R}(n_d - 1)\frac{n_f - n_c}{n_d - 1} = \phi_d \frac{n_f - n_c}{n_d - 1} = \frac{\phi_d}{\nu}$$

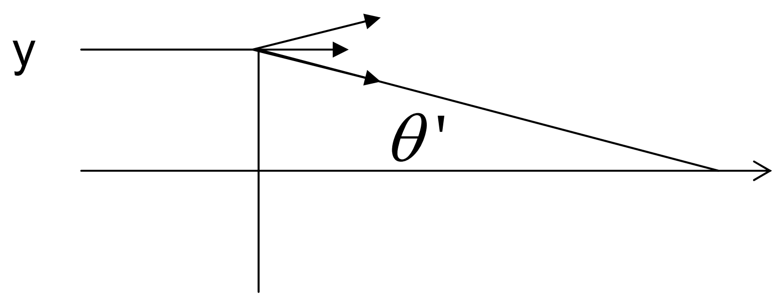
$$\nu_{refractive} = \frac{\phi}{\partial \phi}$$

Diffractive V-number

$$\frac{\Delta\varphi}{\varphi}=\frac{r}{n_d-1}\frac{n_f-n_c}{r}=\frac{n_f-n_c}{n_d-1}=\frac{1}{\nu_{refractive}}$$

$$n'\sin\left(\theta'\right)-n\sin\left(\theta\right)=\frac{m\lambda}{d}$$





$$f=\frac{1}{\varphi}\cong\frac{y}{\sin\left(\theta'\right)}=\frac{y}{m\lambda/d}$$

$$\frac{\Delta\varphi}{\varphi}=\frac{y}{m\lambda_d/d}\frac{m\left(\lambda_f-\lambda_c\right)/d}{y}=\frac{\lambda_f-\lambda_c}{\lambda_d}=\frac{1}{\nu_{diffractive}}\approx\frac{1}{-3.5}$$

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Diffractive focal length from grating perspective

$$f = \frac{1}{\varphi} \cong \frac{y}{\sin(\theta')} = \frac{y}{m\lambda / d}$$

$$= \frac{y}{m\lambda_{construction} / d} \times \frac{\lambda_{construction}}{\lambda_{reconstruction}}$$

$$= f_0 \times \frac{\lambda_{construction}}{\lambda_{reconstruction}}$$

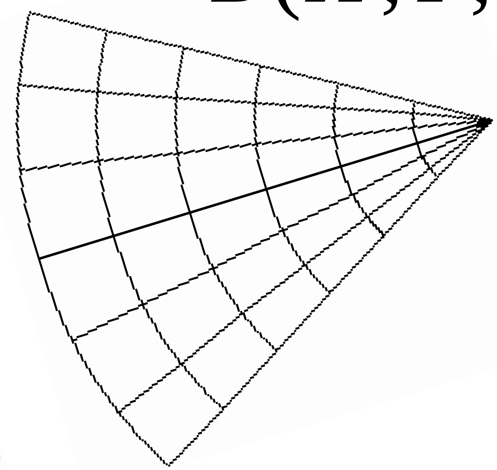
Modeling Diffractive Optics

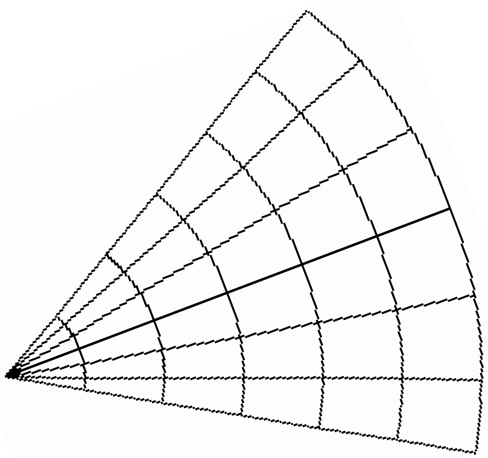
- Two point construction model
- Phase function
- Sweatt model

Two point construction model

$$m, \lambda_{construction}, \lambda_{reconstruction}$$

$$B(X,Y,Z)$$





$$A(X,Y,Z)$$

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Nonparaxial Imaging, Magnification, and Aberration Properties in Holography*

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(Received 9 July 1966)

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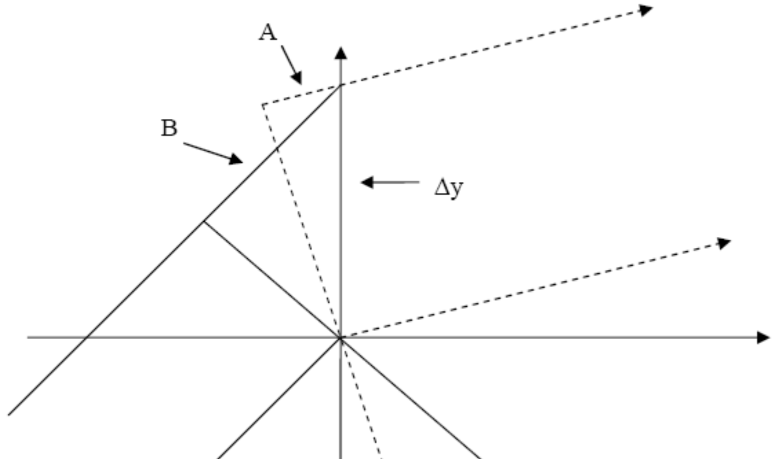
Phase model

$$\phi(\rho) = 2\pi \cdot \left(a\rho^2 + b\rho^4 + c\rho^6 + d\rho^8 + ...\right)$$

$$\rho = \sqrt{x^2 + y^2}$$

Phase model



$$n'\sin(I')\cdot\Delta y = n\sin(I)\cdot\Delta y$$

$$n'\sin(I')\cdot\Delta y - n\sin(I)\cdot\Delta y = \Delta\varphi(y)$$

$$n'\sin(I') - n\sin(I) = \frac{\Delta\varphi(y)}{\Delta y} \rightarrow \frac{\partial\phi(y)}{\partial y}$$

$$\frac{\partial\phi(y)}{\partial y} = n'\sin(I') - n\sin(I)$$

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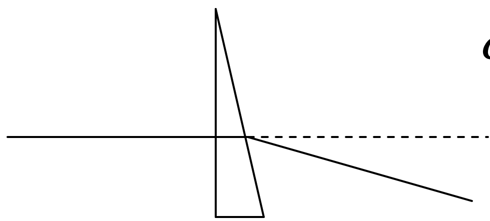
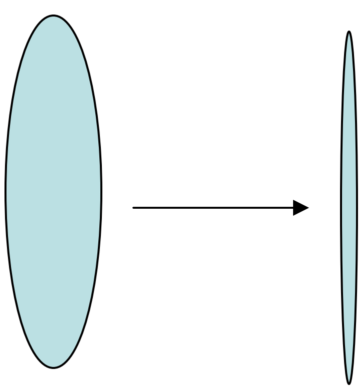
Sweatt’s model



$$\delta = -\alpha(n-1)$$

α

For n~10,000 alpha must be very small to maintain
The same deviation



$$\varphi = \frac{n-1}{r}$$

For a plano convex lens with n~10,000
The radius must be very long to maintain
The same optical power.

Sweatt Model justification

Start with the diffraction grating equation

$$n'\sin(I') - n\sin(I) = \left[n'\cos(I') - n\cos(I)\right] \cdot \frac{m\lambda \quad \text{(1/d)}}{n'\cos(I') - n\cos(I)}$$

$$n'\sin(I') - n\sin(I) = \left[n'\cos(I') - n\cos(I)\right] \cdot \tan(\alpha)$$

$$n'\{\sin(I') - \cos(I')\tan(\alpha)\} = n\{\sin(I) - \cos(I)\tan(\alpha)\}$$

$$n'\{\cos(\alpha)\sin(I') - \cos(I')\sin(\alpha)\} = n\{\cos(\alpha)\sin(I) - \cos(I)\sin(\alpha)\}$$

$$n'\{\sin(I' - \alpha)\} = n\{\sin(I - \alpha)\}$$

Sweatt's Model

$$n'\{\sin(I'-\alpha)\} = n\{\sin(I-\alpha)\}$$

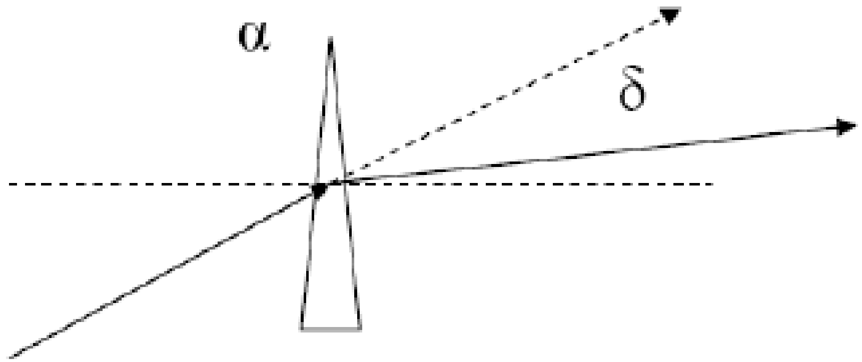
$$\tan(\alpha) = \frac{m\lambda \ \ \text{(1/d)}}{n'\cos(I') - n\cos(I)}$$

For large n's then α is negligible and we have:

$$n'\sin(I) = n\sin(I)$$

Thus for high index diffraction becomes like refraction!

Dispersion in Sweatt's model



$$\delta = -\alpha\left(n-1\right)$$

$$Sin\left(I'\right) \cong Sin\left(I\right) + \left(n_d - 1\right)\alpha$$

$$\Delta \cong Sin\left(I'_F\right) - Sin\left(I'_C\right) \cong \left(n_F - n_C\right)\alpha$$

$$\frac{\delta}{\Delta} = \nu_{refractive} = \frac{\left(n_d - 1\right)\alpha}{\left(n_F - n_C\right)\alpha} = \frac{\lambda_d\left(10,000\right)}{\lambda_F\left(10,000\right) - \lambda_C\left(10,000\right)} = \frac{\lambda_d}{\lambda_F - \lambda_C} \cong -3.5$$

Dispersion in Sweatt's model

Consistent with diffraction case

$$Sin(I'_d) - Sin(I_d) = \frac{m\lambda_d}{d} \cong \delta$$

$$\Delta \cong Sin(I'_F) - Sin(I'_C) = m\frac{\lambda_F - \lambda_C}{d}$$

$$\frac{\delta}{\Delta} = \nu_{refractive} \cong \frac{m\dfrac{\lambda_d}{d}}{m\dfrac{\lambda_F - \lambda_C}{d}} = \frac{\lambda_d}{\lambda_F - \lambda_C}$$

In conclusion:

To include dispersion in the Sweatt model make the index of refraction equal to the wavelength times 10,000

Schott: $n(\lambda)^2 = A + B\lambda^2 + \ldots$

Structural coefficients: Thin lens (stop at lens)

$$A=\frac{n+2}{n(n-1)^2}$$

$$S_I=\frac{1}{4}y^4\phi^3\left[AX^2-BXY+CY^2+D\right]$$

$$B=\frac{4(n+1)}{n(n-1)}$$

$$S_{II}=\frac{1}{2}\text{Ж}y^2\varphi^2\left[EX-FY\right]$$

$$S_{III}=\text{Ж}^2\varphi$$

$$C=\frac{3n+2}{n}$$

$$S_{IV}=\text{Ж}^2\varphi\frac{1}{n}$$

$$X=\frac{c_1+c_2}{c_1-c_2}=\frac{r_2+r_1}{r_2-r_1}$$

$$D=\frac{n^2}{(n-1)^2}$$

$$S_V=0$$

$$Y=\frac{1+m}{1-m}=\frac{u'+u}{u'-u}$$

$$E=\frac{n+1}{n(n-1)}$$

$$C_L=y^2\phi\frac{1}{\nu}$$

$$\phi=\Delta n\Delta c=(n-1)(c_1-c_x)$$

$$C_T=0$$

$$F=\frac{2n+1}{n}$$

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Diffractive lens
(n very large @ X=0)

Structural aberration coefficients of a thin lens (Stop at lens)	
Paraxial identities	
$\phi = (n'-n)\cdot(c_1 - c_2) = (n'-n)\cdot\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$	
$X = \frac{c_1 + c_2}{c_1 - c_2} = -\frac{R_1 + R_2}{R_1 - R_2}$	$Y = \frac{w'+w}{w'-w} = \frac{1+m}{1-m}$
$c_1 = \frac{1}{2}\frac{\phi}{n-1}(X+1)$	$c_2 = \frac{1}{2}\frac{\phi}{n-1}(X-1)$
$w = u = -\frac{1}{2}(Y-1)(\phi\cdot y)$	$w' = u' = -\frac{1}{2}(Y+1)(\phi\cdot y)$
Structural aberration coefficients	
$\sigma_I = AX^2 - BXY + CY^2 + D$	$A = \frac{n+2}{n(n-1)^2}$
$\sigma_{II} = EX - FY$	$B = \frac{4(n+1)}{n(n-1)}$
$\sigma_{III} = 1$	$C = \frac{3n+2}{n}$
$\sigma_{IV} = \frac{1}{n}$	$D = \frac{n^2}{(n-1)^2}$
$\sigma_V = 0$	$E = \frac{n+1}{n(n-1)}$
$\sigma_L = \frac{1}{\nu}$	$F = \frac{2n+1}{n}$
$\sigma_T = 0$	

$$\sigma_I = 3Y^2 + 1$$

$$\sigma_{II} = -2Y$$

$$\sigma_{III} = 1$$

$$\sigma_{IV} = 0$$

$$\sigma_V = 0$$

$$\sigma_L = \frac{1}{\nu_{diffractive}}$$

$$\sigma_T = 0$$

C=3; D=1; F=2

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Aberration coefficients for Y=1; X=0

$$S_I = \frac{y^4}{f^3}\left(\frac{\lambda}{\lambda_0}\right)^3$$

$$S_{III} = \frac{Ж^2}{f}\left(\frac{\lambda}{\lambda_0}\right)$$

$$S_V = 0$$

$$S_{II} = \frac{-y^2}{f^2} Ж \left(\frac{\lambda}{\lambda_0}\right)^2$$

$$S_{IV} = 0$$

For general case one needs to be careful as the shape depends on the index for a given power.

Structural coefficients for diffractive lens

Structural aberration coefficients of a thin lens (Stop at lens)	
Paraxial identities	
$\phi = (n' - n)\cdot(c_1 - c_2) = (n' - n)\cdot\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$	
$X = \frac{c_1 + c_2}{c_1 - c_2} = -\frac{R_1 + R_2}{R_1 - R_2}$	$Y = \frac{w' + w}{w' - w} = \frac{1 + m}{1 - m}$
$c_1 = \frac{1}{2}\frac{\phi}{n-1}(X+1)$	$c_2 = \frac{1}{2}\frac{\phi}{n-1}(X-1)$
$w = u = -\frac{1}{2}(Y-1)(\phi\cdot y)$	$w' = u' = -\frac{1}{2}(Y+1)(\phi\cdot y)$
Structural aberration coefficients	
$\sigma_I = AX^2 - BXY + CY^2 + D$	$A = \frac{n+2}{n(n-1)^2}$
$\sigma_{II} = EX - FY$	$B = \frac{4(n+1)}{n(n-1)}$
$\sigma_{III} = 1$	$C = \frac{3n+2}{n}$
$\sigma_{IV} = \frac{1}{n}$	$D = \frac{n^2}{(n-1)^2}$
$\sigma_V = 0$	$E = \frac{n+1}{n(n-1)}$
$\sigma_L = \frac{1}{\nu}$	$F = \frac{2n+1}{n}$
$\sigma_T = 0$	

$$\sigma_I = \frac{4}{(\phi R_2)^2} - \frac{8Y}{\phi R_2} + 3Y^2 + 1$$

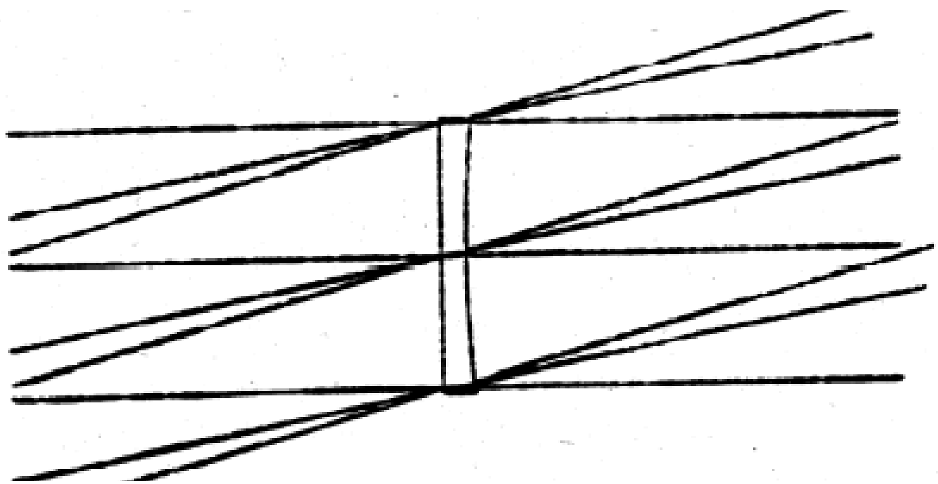
$$\sigma_{II} = \frac{2}{\phi R_2} - 2Y$$

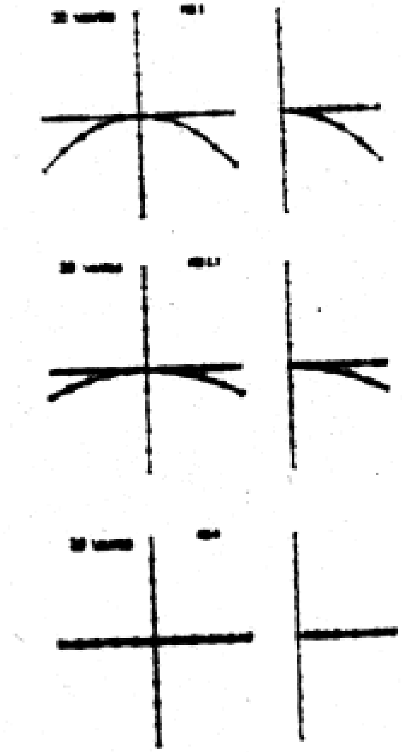
$$\sigma_{IV} = 0 \qquad \sigma_V = 0$$

$$\sigma_L = \frac{1}{\nu_{diffractive}}$$

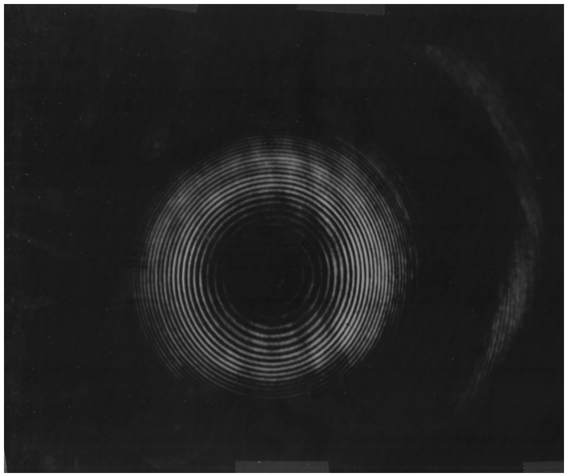
$$\sigma_T = 0 \qquad \sigma_{III} = 1$$

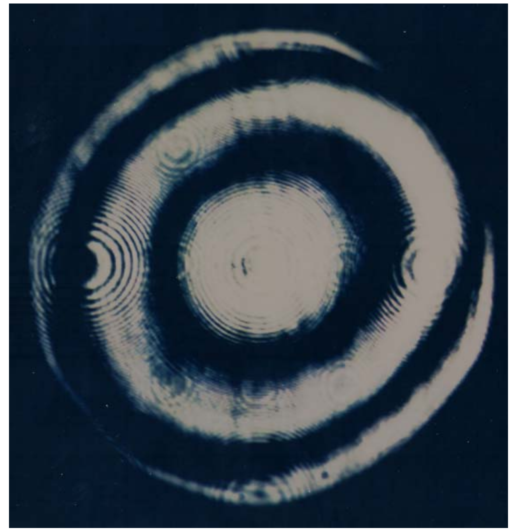
Field curvature correction hybrid lens

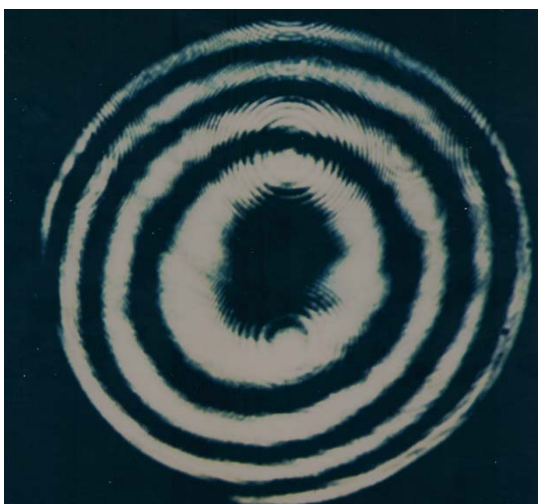


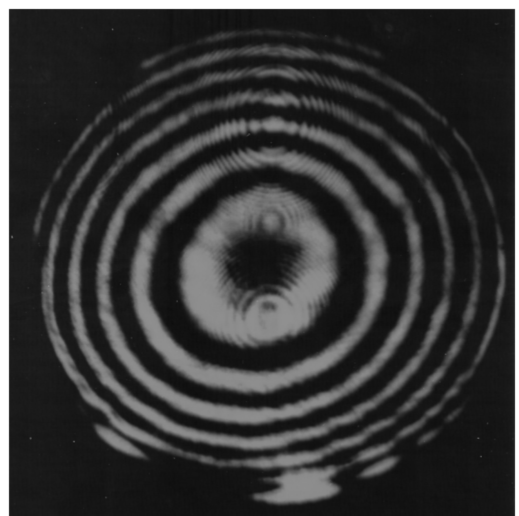


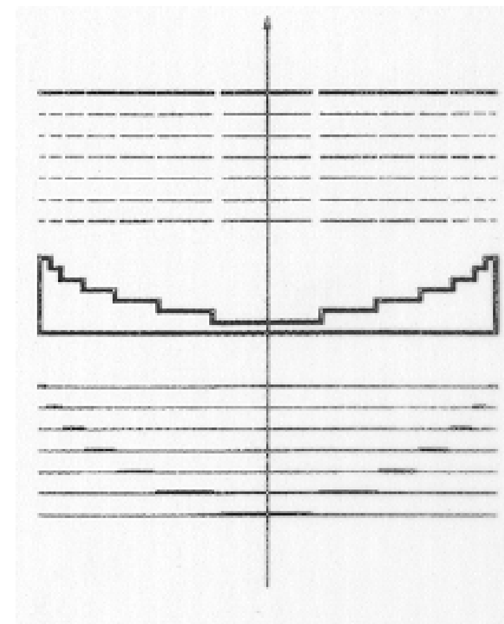
Verification











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OPD Alternate view

- OPD has two parts. One is due to material dispersion, the other to due to diffraction

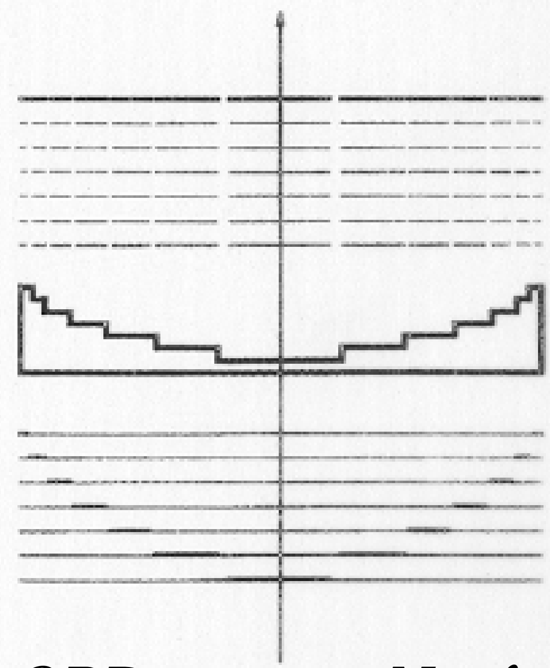
$$OPD_F = \frac{y^2}{2R}\left(\left(n_F - 1\right) + \left(n_d - 1\right)\frac{\lambda_F}{\lambda_d}\right)$$

$$OPD_F - OPD_C = \frac{y^2}{2R}\left(\left(n_F - 1\right) + \left(n_d - 1\right)\frac{\lambda_F}{\lambda_d}\right)$$

$$-\frac{y^2}{2R}\left(\left(n_C - 1\right) + \left(n_d - 1\right)\frac{\lambda_C}{\lambda_d}\right)$$

$$= \frac{y^2}{2R}\left(\left(n_F - n_C\right) + \left(n_d - 1\right)\frac{\lambda_F - \lambda_C}{\lambda_d}\right)$$

$$= \frac{y^2}{2}\phi\left(\frac{1}{\nu_{ref}} + \frac{1}{\nu_{diff}}\right)$$



$$OPD = n \times t + N \times \lambda$$

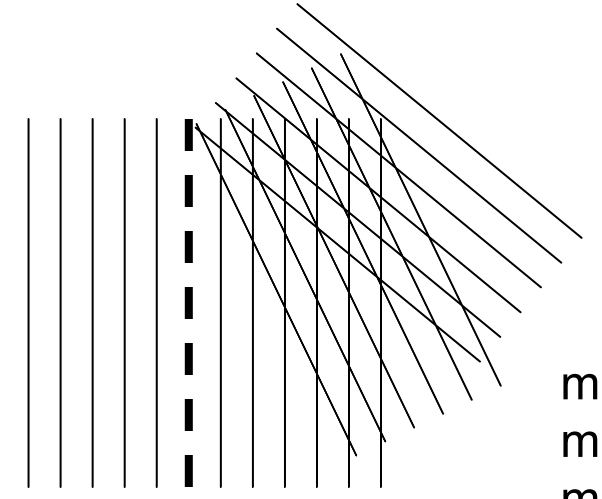
Spherical aberration

- Depending on the zone boundary distribution DOE axially symmetric DOE can introduce different orders of spherical aberration

$$\phi(\rho) = 2\pi \cdot \left(a\rho^2 + b\rho^4 + c\rho^6 + d\rho^8 + ...\right)$$

Calculating order efficiency

- Simple case of an amplitude device with a square wave profile
- Duty cycle



$$\psi(x,y) = A_p Comb(x - nx_0) ** rect\left(\frac{x}{d}\right)$$

Square wave

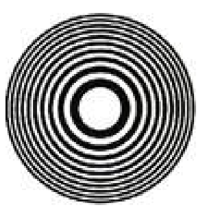
$$F(\nu) \cong \frac{A}{2} SINC\left(\frac{\nu}{2\nu_0}\right) \sum_{-\infty}^{\infty} \partial(\nu - n\nu_0) = \frac{A}{2} \sum_{-\infty}^{\infty} SINC\left(\frac{n}{2}\right) \partial(\nu - n\nu_0)$$

$$f(t) = square\ \ wave = \frac{A}{2} \sum_{-\infty}^{\infty} SINC\left(\frac{n}{2}\right) e^{i2\pi n\nu_0 t}$$

$$= \frac{A}{2} + \frac{A}{\pi}\left[e^{i2\pi n\nu_0 t} + e^{-i2\pi n\nu_0 t}\right] + \frac{A}{3\pi}\left[e^{i2\pi n3\nu_0 t} + e^{-i2\pi n3\nu_0 t}\right]$$

$$+ \frac{A}{5\pi}\left[e^{i2\pi n5\nu_0 t} + e^{-i2\pi n5\nu_0 t}\right] + \frac{A}{7\pi}\left[e^{i2\pi n7\nu_0 t} + e^{-i2\pi n7\nu_0 t}\right] + \ldots$$

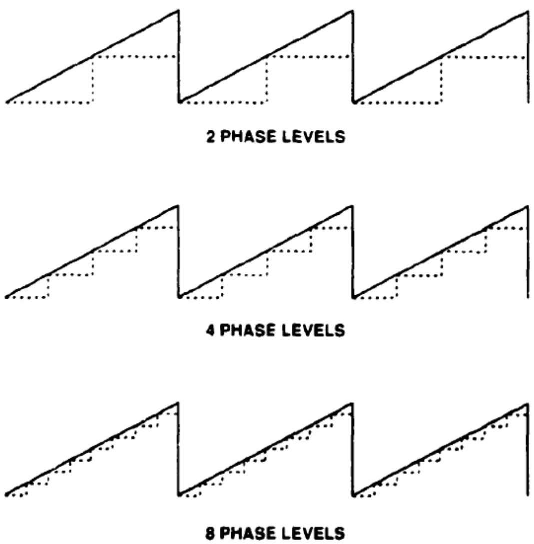
$$\nu_0 = T^{-1}$$

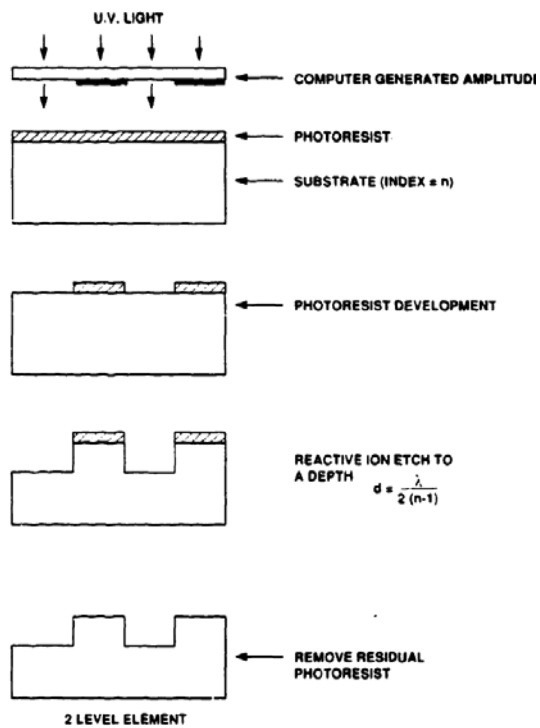


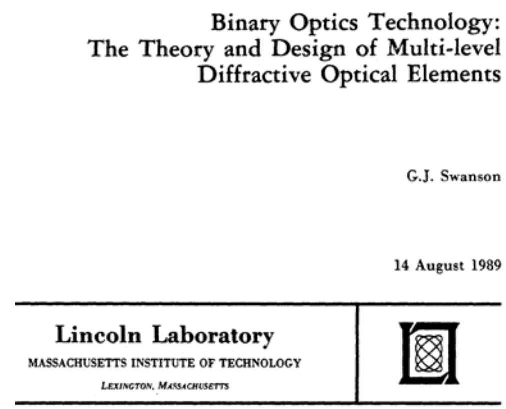
50% duty cycle

$$\left(\frac{1}{\pi}\right)^2 \approx 0.1$$

Binary optics technology





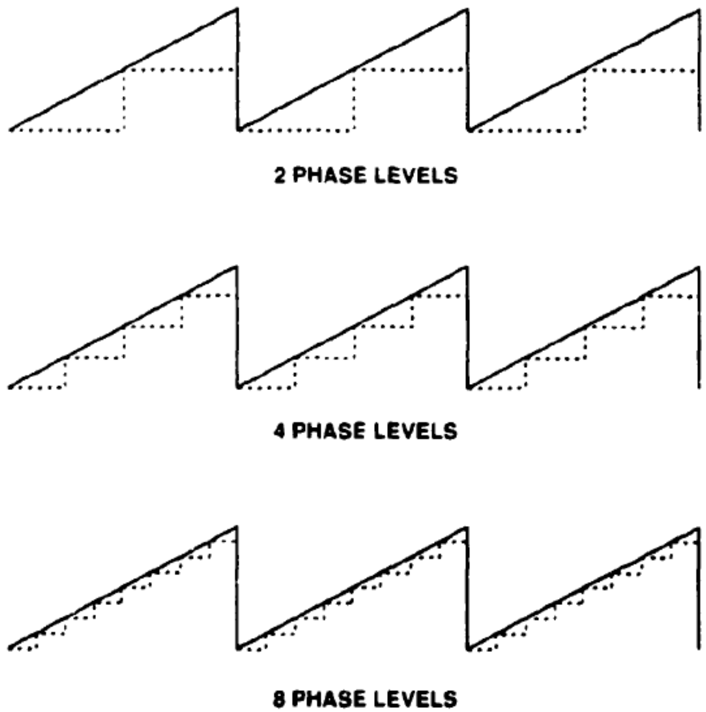

Binary Optics Technology:
The Theory and Design of Multi-level
Diffractive Optical Elements

G.J. Swanson

14 August 1989

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

Efficiency for binary optics



$$\eta_1^{N} = \left[\frac{\sin(\pi / N)}{\pi / N} \right]^2$$

Number of Levels N	First-Order Efficiency η_1^{N}
2	0 41
3	0.68
4	0.81
5	0.87
6	0.91
8	0.95
12	0.98
16	0.99

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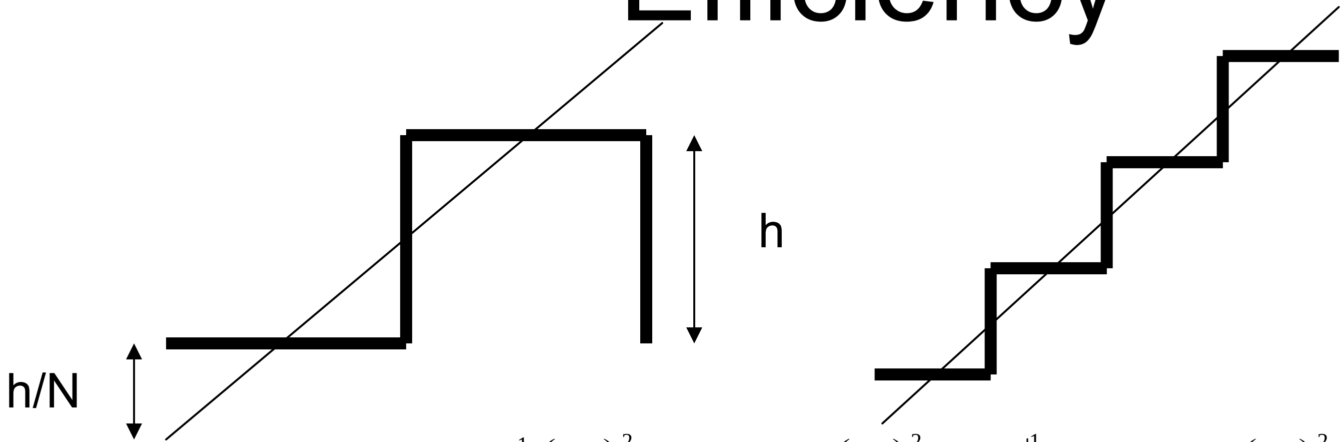
Efficiency



$$\sigma^2 = (n-1)^2 \frac{1}{2}\int_{-1}^{1}\left(\frac{hx}{N}\right)^2 dx = (n-1)^2\left(\frac{h}{N}\right)^2 \frac{1}{2} x^3 \frac{1}{3}\Big|_{-1}^{1} = \frac{1}{3}(n-1)^2\left(\frac{h}{N}\right)^2$$

$$h = 1$$

$$(n-1)2h = \lambda$$

$$\sigma^2 = \frac{1}{3}\frac{4}{4}(n-1)^2\left(\frac{h}{N}\right)^2 = \frac{1}{12}\lambda^2\left(\frac{1}{N}\right)^2$$

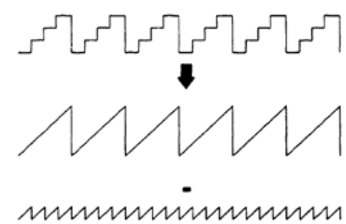
$$S \approx 1 - \frac{\pi^2}{3}\left(\frac{1}{N}\right)^2$$

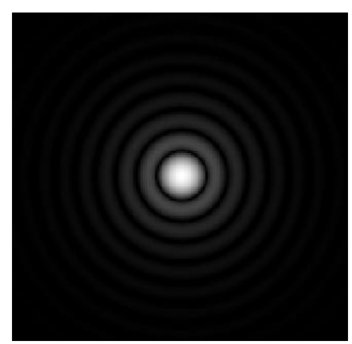
$$N = 2\ ; S = 0.17$$

$$N = 4\ ; S = 0.794$$

$$N = 8\ ; S = 0.948$$

$$N = 16\ ; S = 0.987$$





$$S \approx 1 - \left(\frac{2\pi}{\lambda}\sigma\right)^2$$

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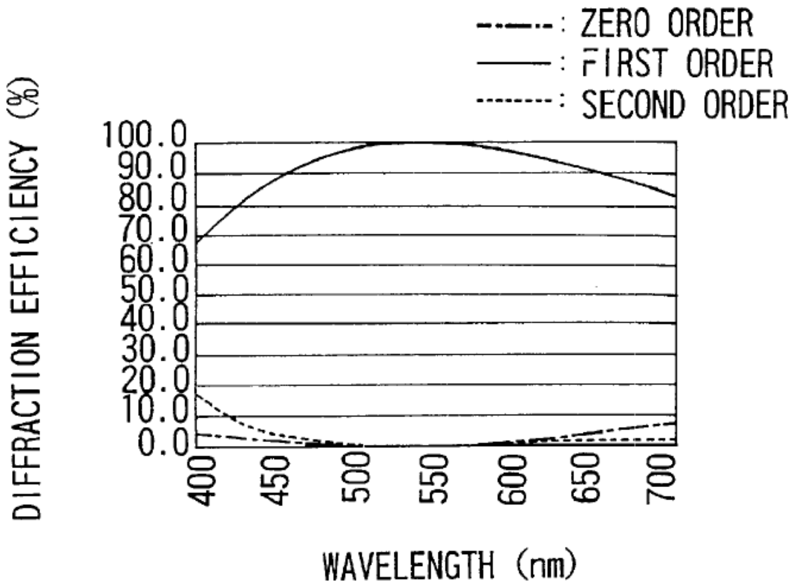
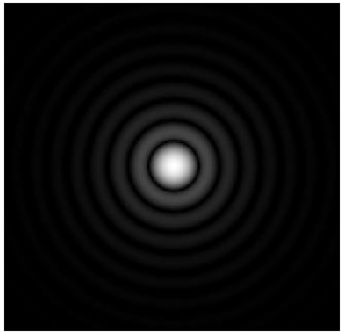
Efficiency

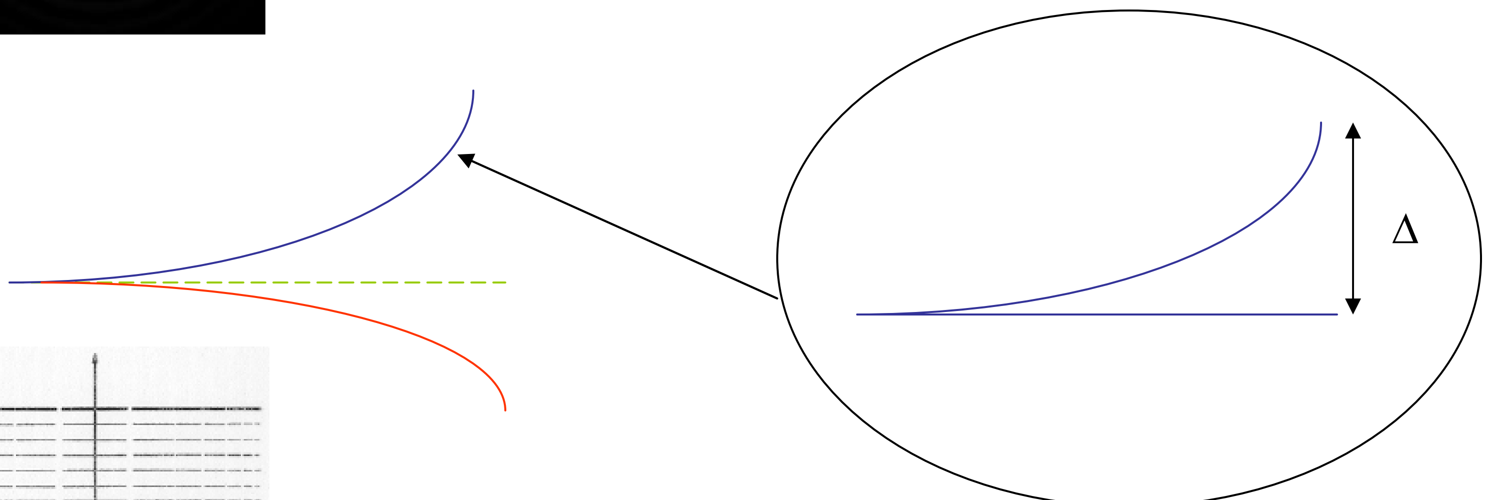
$$\varepsilon = \operatorname{sinc}^2\left(\pi\left[\frac{\lambda_{construction}}{\lambda_{reconstruction}}\frac{n(\lambda_{reconstruction})-1}{n(\lambda_{construction})-1} - m\right]\right)$$

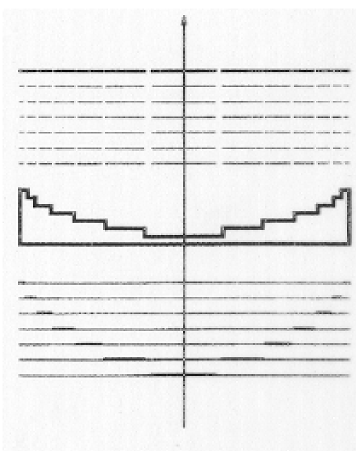


Efficiency



$$\varepsilon \approx 1-\left(\frac{2\pi}{\lambda}\sigma\right)^2 \approx 1-\left(\frac{2\pi}{\lambda_{reconstruction}}\frac{\lambda_{reconstruction}-\lambda_{construction}}{3}\right)^2$$



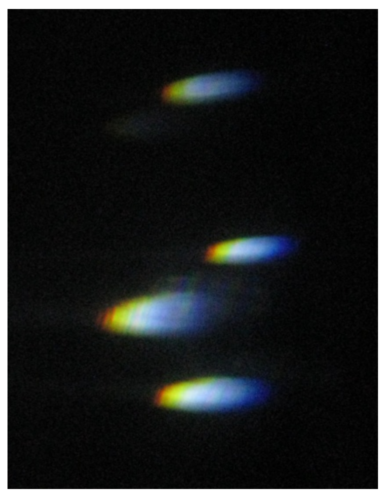


$$\Delta \approx \lambda_{reconstruction} - \lambda_{construction}$$

Comparison

Standard lens, Fresnel lens and DOE lens

Refracting lens



Fresnel lens

DOE lens

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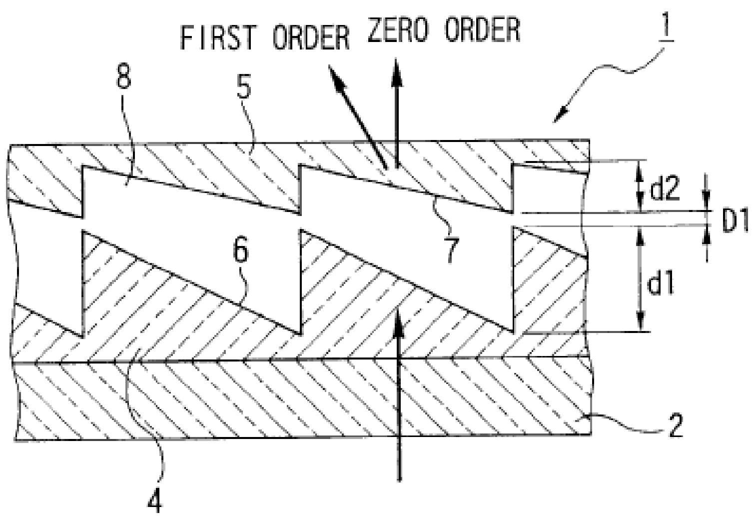
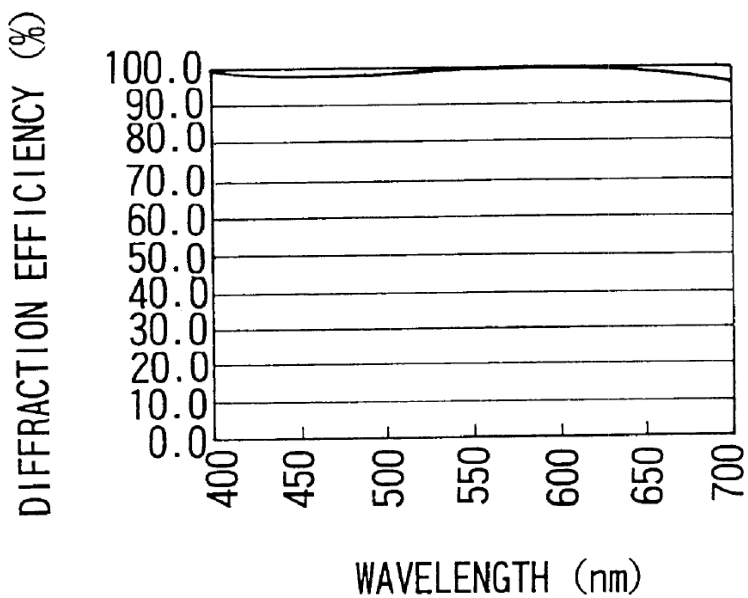
Images of extended objects

Acrylic powerless lens

Other orders produce images at different magnifications
Like ghost images

Canon’s multilayer DOE’s





How does it work?

US006507437B1

(12) **United States Patent**
Nakai

(10) **Patent No.: US 6,507,437 B1**
(45) **Date of Patent: *Jan. 14, 2003**

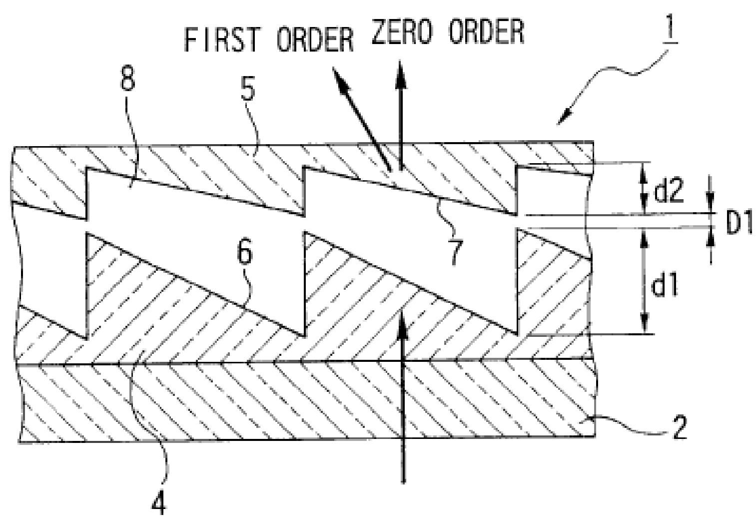
(54) **DIFFRACTIVE OPTICAL ELEMENT AND PHOTOGRAPHIC OPTICAL SYSTEM HAVING THE SAME**

(75) Inventor: **Takehiko Nakai**, Kawasaki (JP)

(73) Assignee: **Canon Kabushiki Kaisha**, Tokyo (JP)

FOREIGN PATENT DOCUMENTS

JP	4-213421	8/1992
JP	6-324262	11/1994
JP	9-127322	5/1997
JP	10-104411	4/1998
JP	10-133149	5/1998



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How does it work?

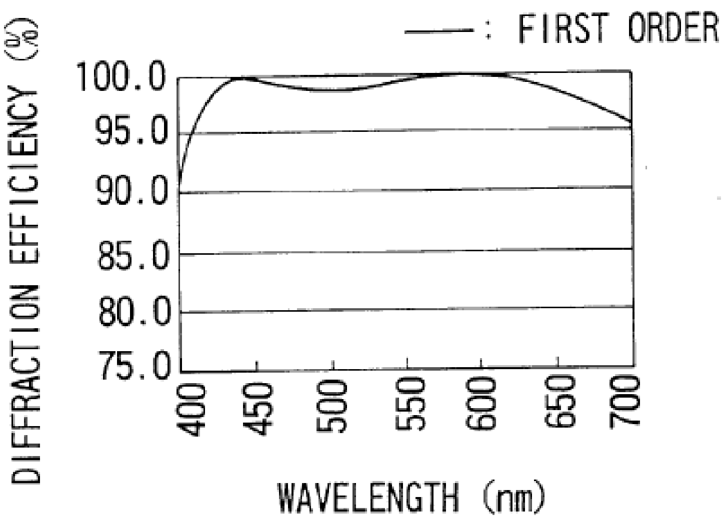
$$\varepsilon(\lambda) = \operatorname{sinc}^2\left(\pi\left[\frac{\lambda_{construction}}{\lambda_{reconstruction}}\frac{n(\lambda_{reconstruction})-1}{n(\lambda_{construction})-1} - m\right]\right)$$

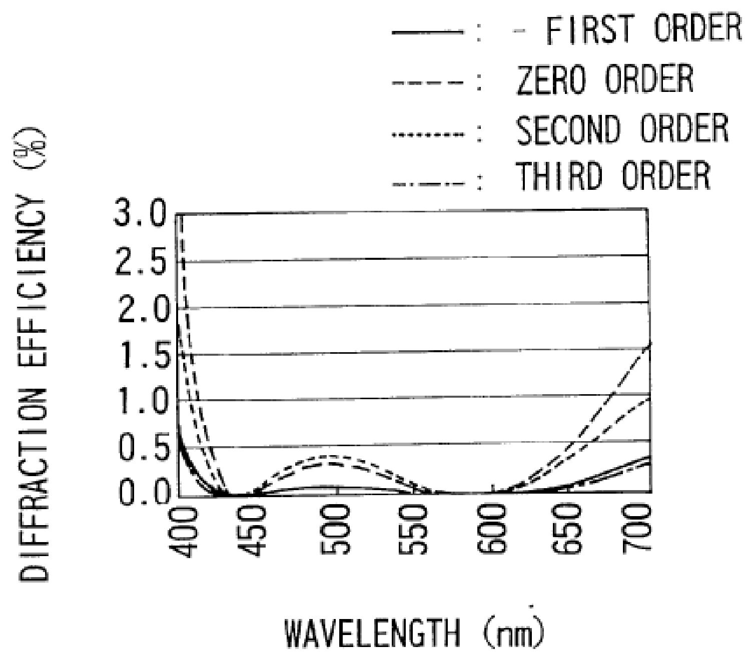
$$\varepsilon(\lambda) = \operatorname{sinc}^2\left(\pi\left[d\,\frac{n(\lambda_{reconstruction})-1}{\lambda_{reconstruction}} - m\right]\right) = \operatorname{sinc}^2\left(\pi\left[\frac{d_{construction}}{d_{reconstruction}} - m\right]\right)$$

$$\varepsilon(\lambda) = \operatorname{sinc}^2\left(\pi\left[d_2\,\frac{n_2(\lambda_{reconstruction})-1}{\lambda_{reconstruction}} \pm d_1\,\frac{n_1(\lambda_{reconstruction})-1}{\lambda_{reconstruction}} - m\right]\right)$$

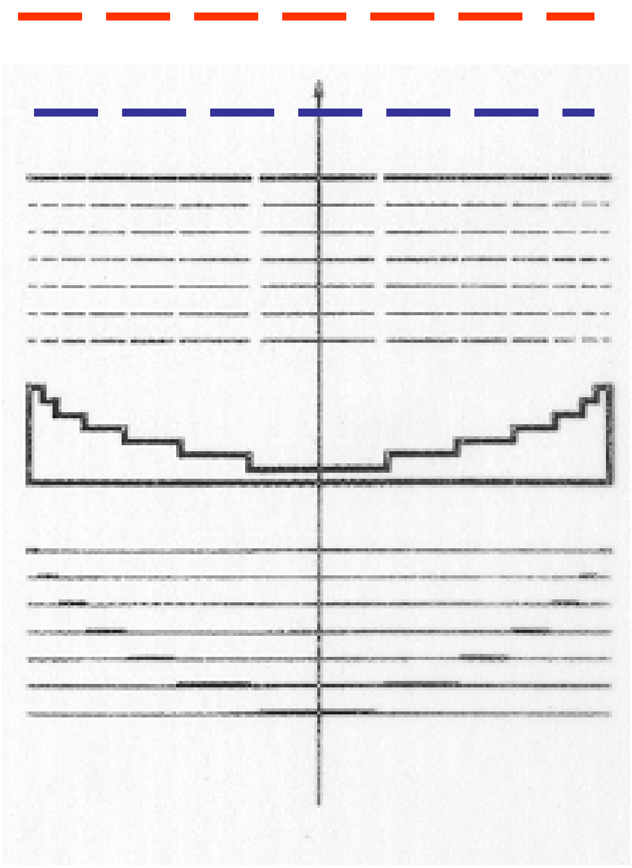
$$or\;\; d_2\left(n_2(\lambda_{reconstruction})-1\right) \pm d_1\left(n_1(\lambda_{reconstruction})-1\right) = \lambda_{reconstruction}$$

100% at two wavelengths

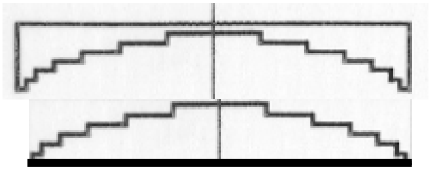


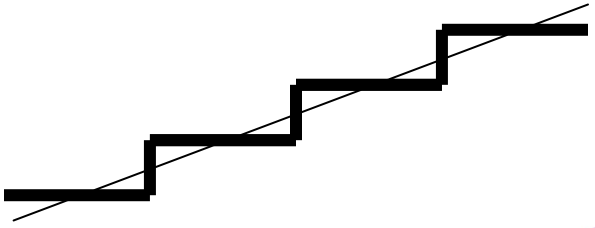


Alternate view
100% efficiency at 2λ (no ripple)



$$\lambda_2 = 2\lambda_1 = 2\left(450nm\right)$$





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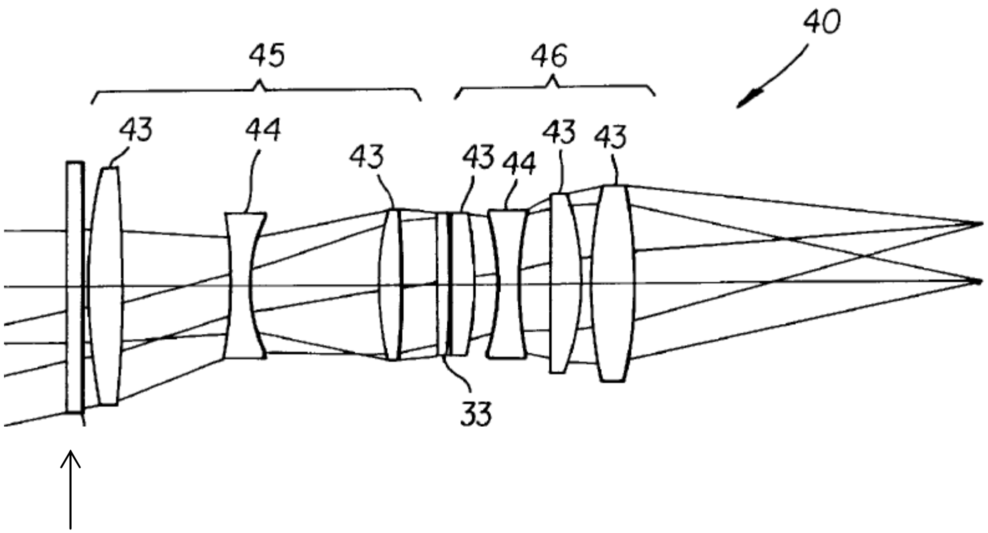
An actual lens application for controlling chromatic change of magnification



DOE

(12) **United States Patent**
Harrigan

(54) **MOVIE PROJECTION LENS**

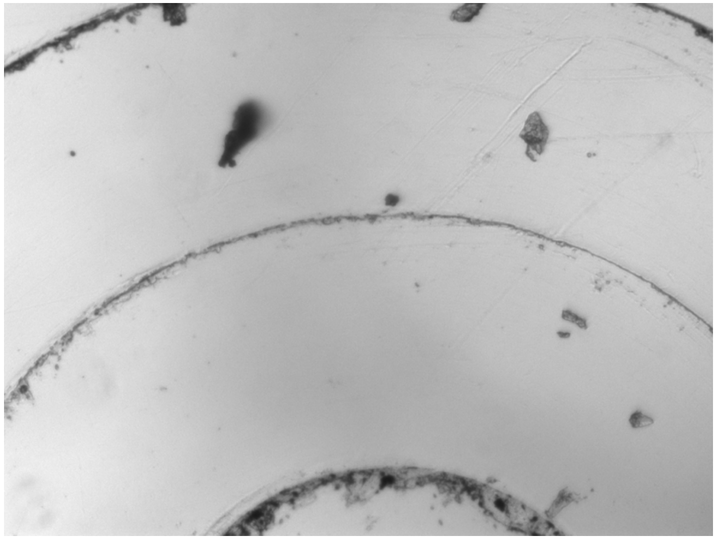
(75) Inventor: **Michael Harrigan**, Webster, NY (US)

(73) Assignee: **Eastman Kodak Company**, Rochester, NY (US)

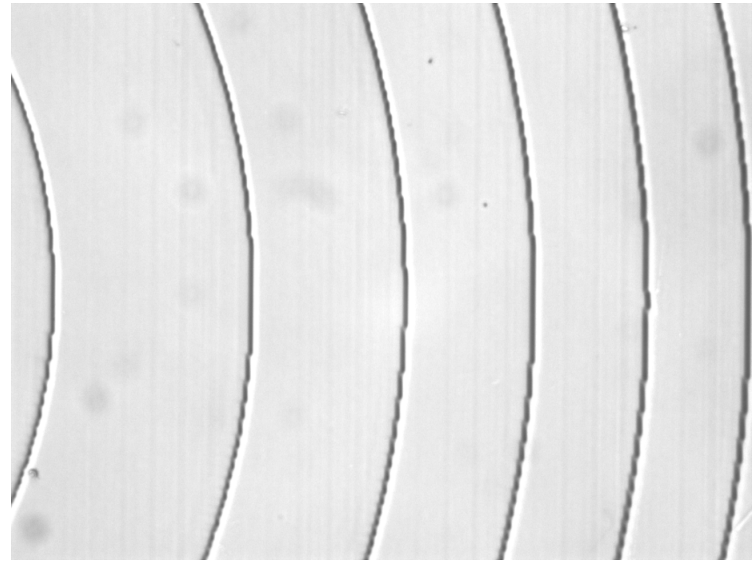
(10) **Patent No.: US 6,317,268 B1**
(45) **Date of Patent: Nov. 13, 2001**

Note lack of lens symmetry about the stop

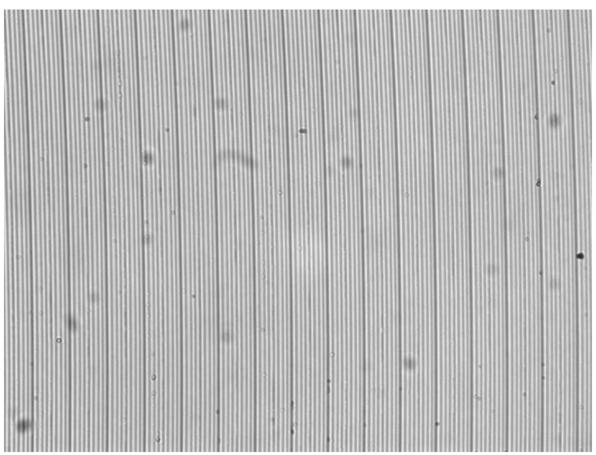
Some Fresnel lens and DOE photographs



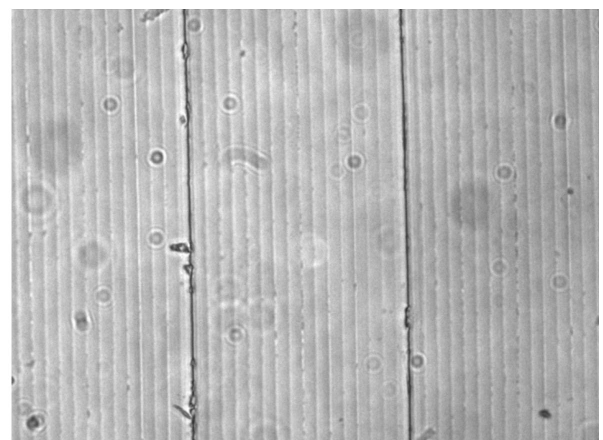
Plastic Fresnel lens;
Diamond turned and replicated



Gray scale; note binary edge



Binary 8 levels



Binary 16 levels

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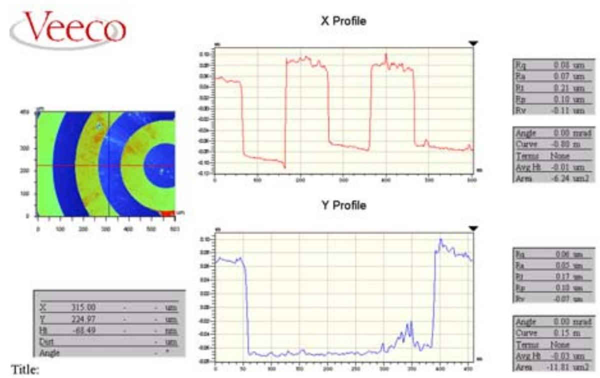
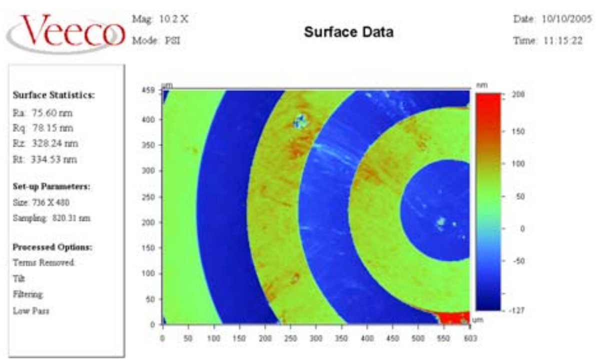
Measurement of a DOE





3-Dimensional Interactive Display

Date: 10/10/2005

Time: 11:15:22

Surface Stats:

Ra: 75.60 nm

Rq: 78.15 nm

Rt: 334.53 nm

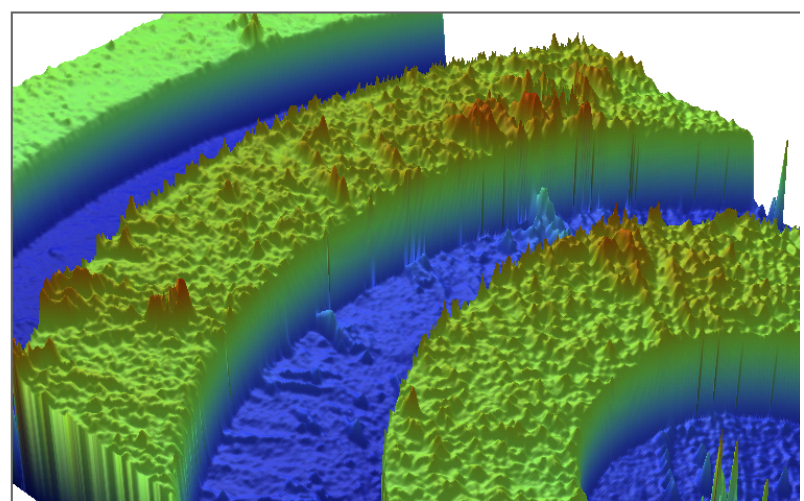
Measurement Info:

Magnification: 10.24

Measurement Mode: PSI

Sampling: 820.31 nm

Array Size: 736 X 480



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Beware

- Modeling assumes DOEs having no physical structure
- Real modeling faces sampling issues
- Scalar treatment
- Zones are about ~7λ or more
- Light scattered at boundaries and zone shadowing effects
- Fabrication: Diamond turning, microlithography printing techniques, Grey scale techniques.

Examples

- Diffractive landscape lens
- Correction of chromatic change in the landscape lens, eyepieces, fish-eye lenses, unsymmetrical lenses
- Null-corrector Certifier
- Modeling a few zones