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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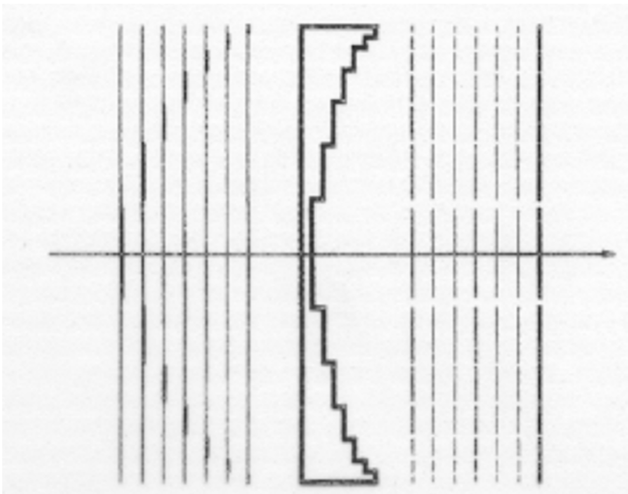
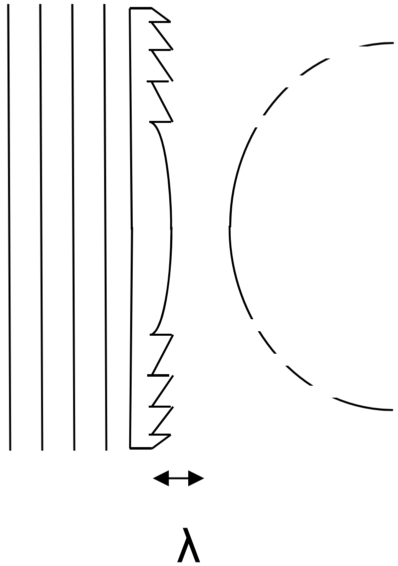
Terminology

- 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

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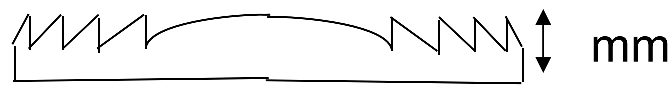
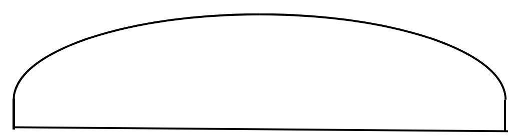
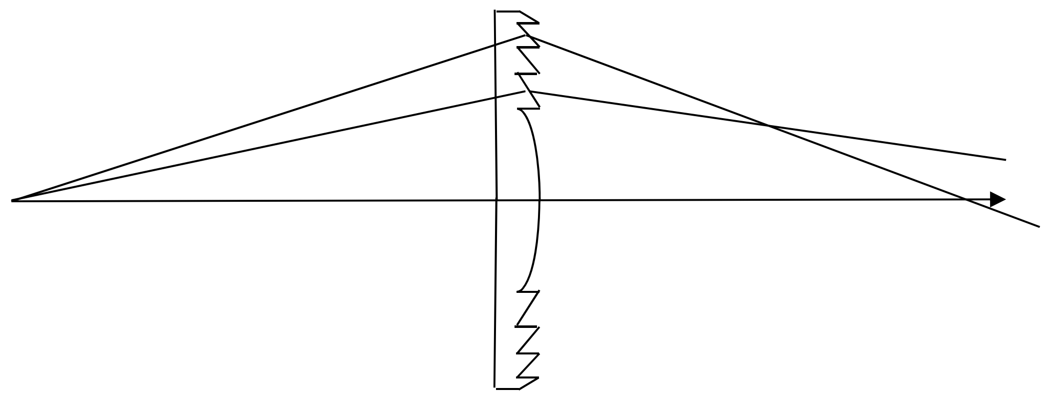
Fresnel Lens







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 zones may have equal width too.
The ring-zone segments are not properly organized.

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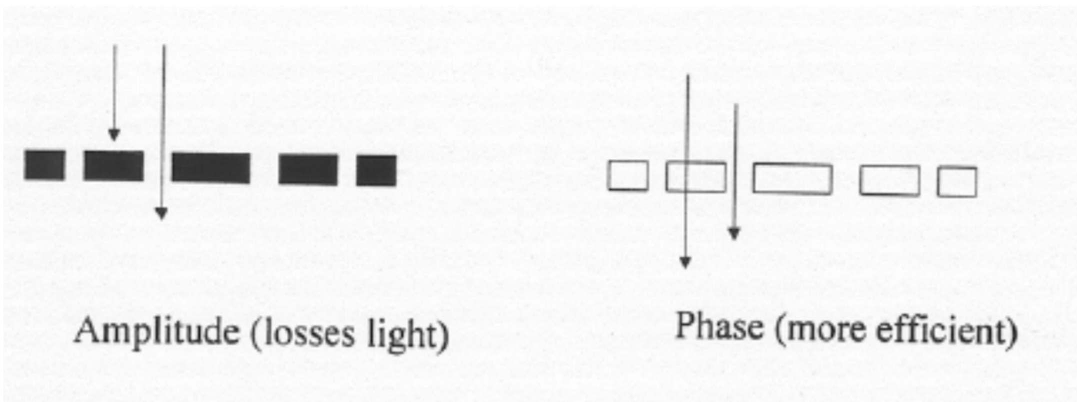
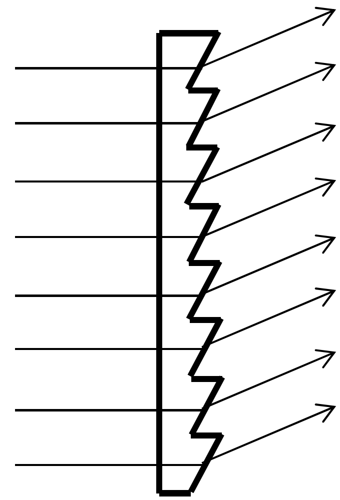
Two contexts for DOE: amplitude and phase





- 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

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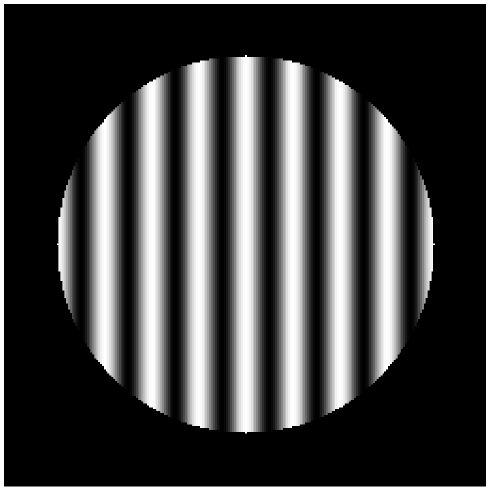
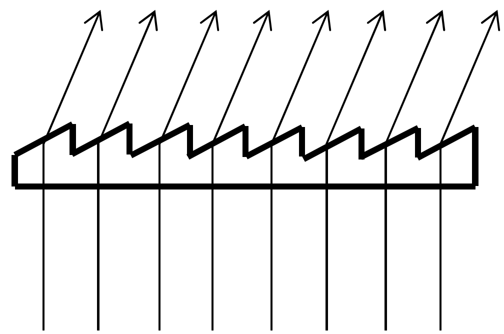
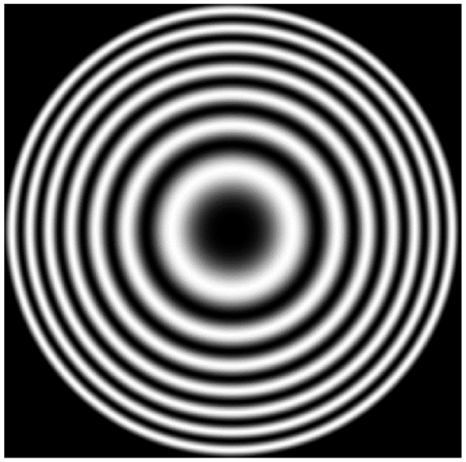
Example

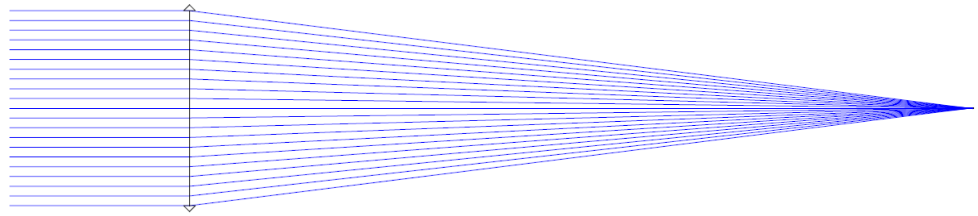


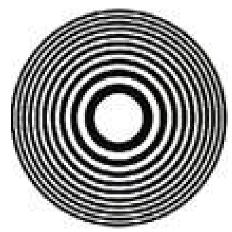


- Straight fringes represent tilt and so the beam is deviated

Example





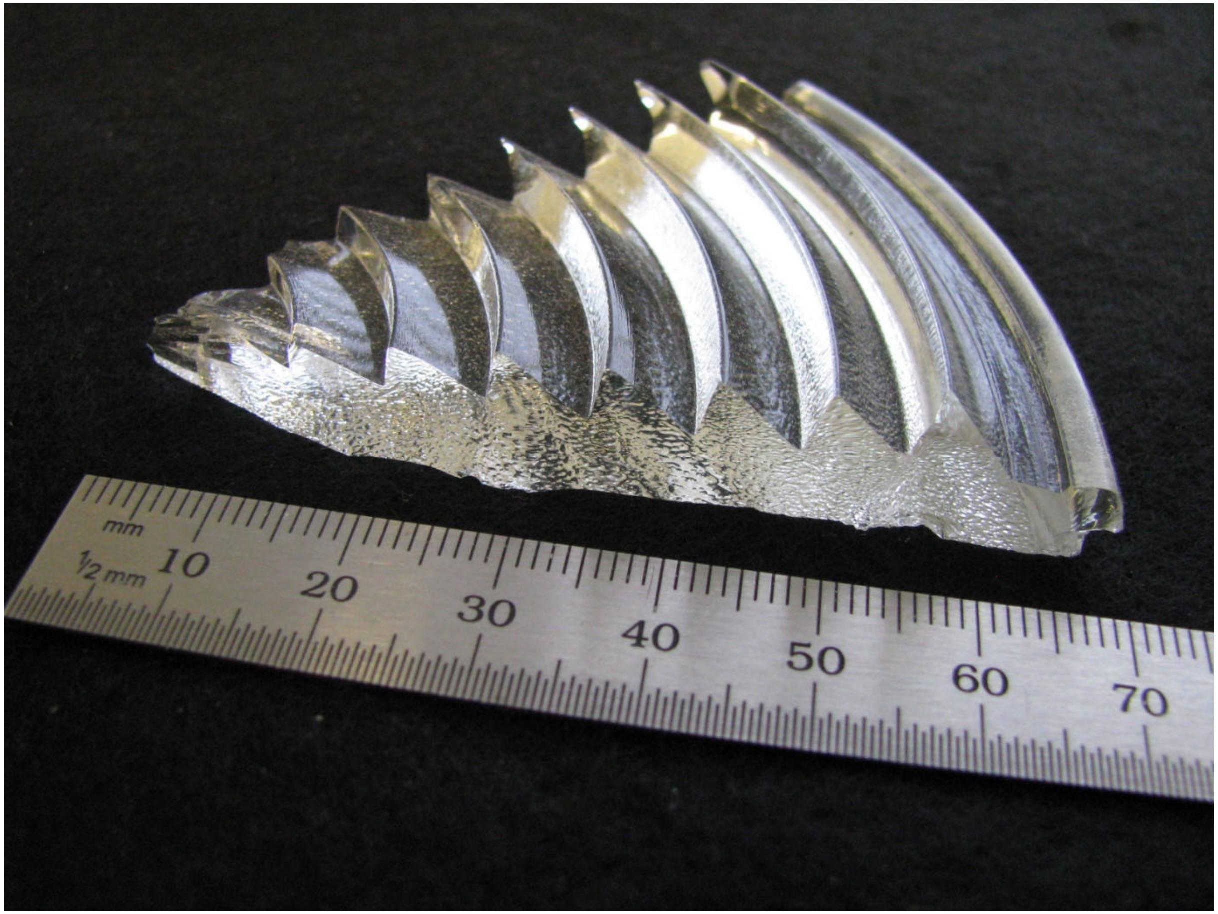


- Circular fringes represent defocus and so a DOE with these zone boundaries will introduce optical power
- Depending on the spacing, spherical aberration can also be introduced

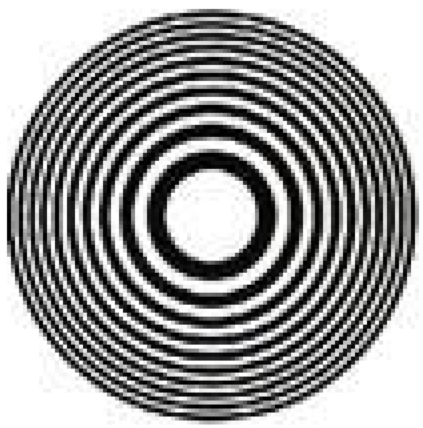
An infrared DOE

From Michael Morris

A Fresnel lens cut-away



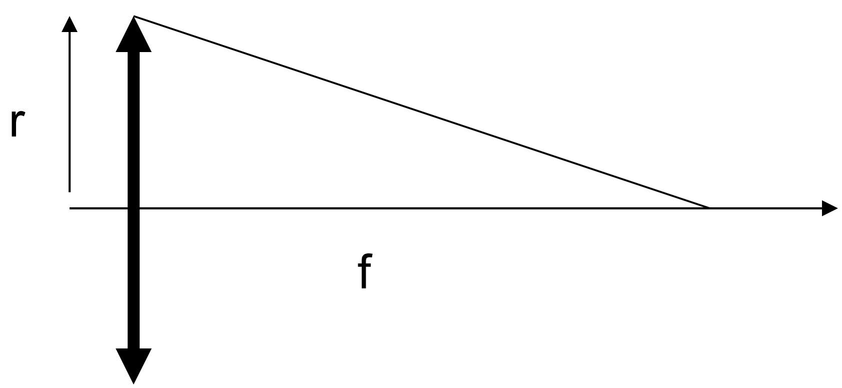
First-order properties



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

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

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



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

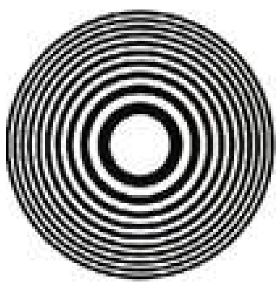
Dale A. Buralli and G. Michael Morris

Zone Spacing

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

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

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



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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

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

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

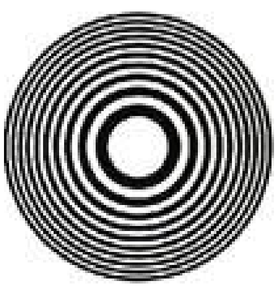
$$\partial \phi = \frac{1}{R}(n_d - 1)\frac{n_f - n_c}{n_d - 1} = \phi_d \frac{n_f - n_c}{n_d - 1} = \frac{\phi_d}{\nu}$$

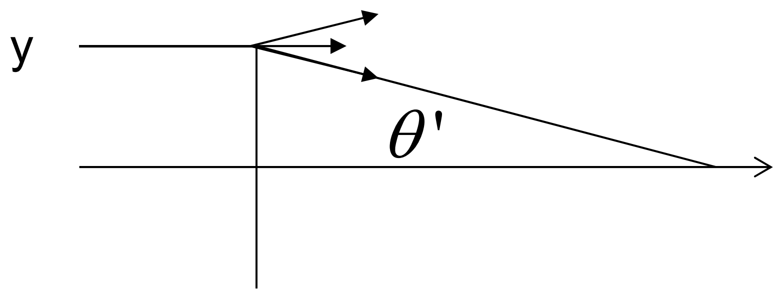
$$\nu_{refractive} = \frac{\phi}{\partial \phi}$$

Diffractive V-number

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

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





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

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

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Diffractive focal length from grating perspective

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

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

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

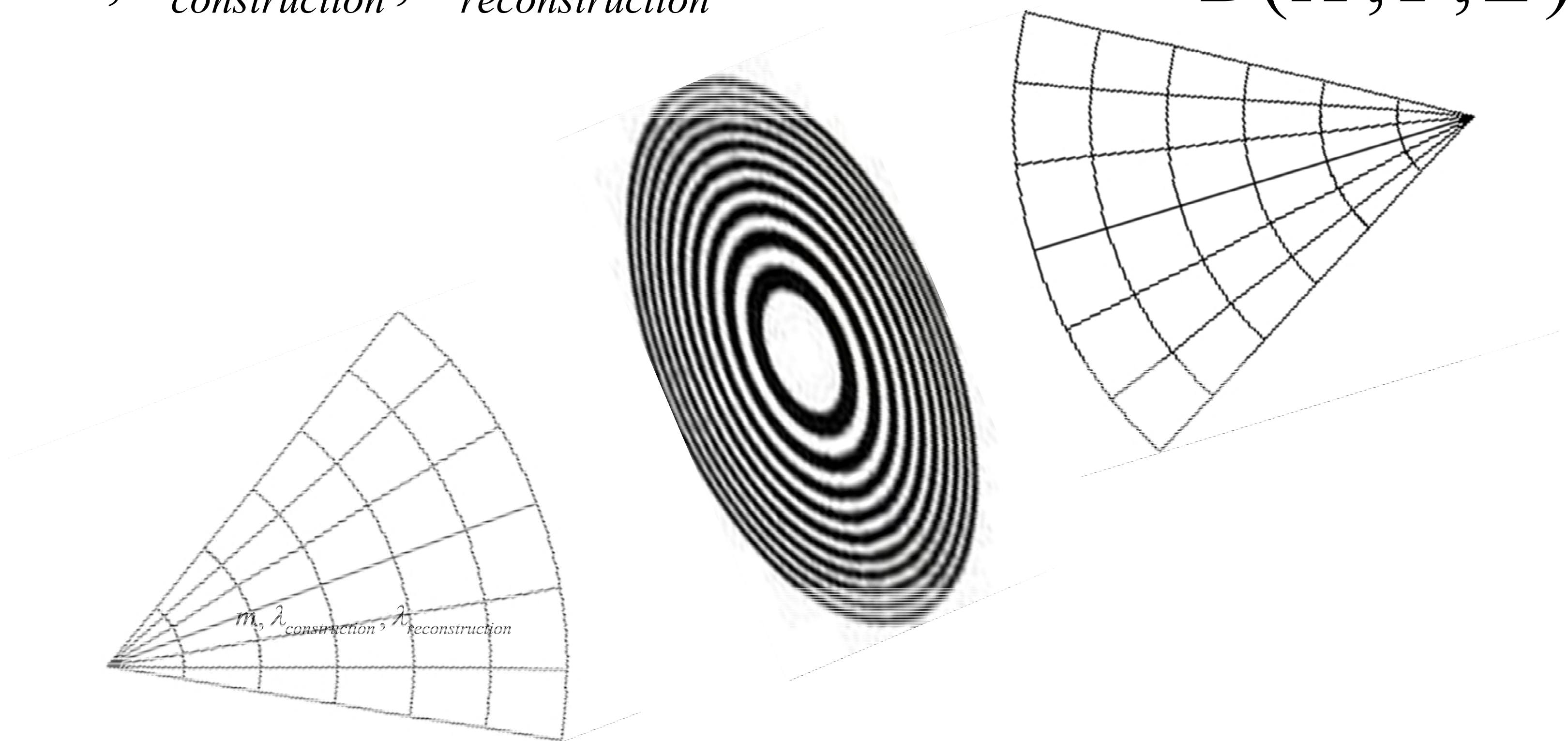
Modeling Diffractive Optics

- Two point construction model
- Phase function
- Sweatt model

Two point construction model

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

$B(X, Y, Z)$



$A(X, Y, Z)$

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 57, NUMBER 1 JANUARY 1967

Nonparaxial Imaging, Magnification, and Aberration Properties in Holography*

EDWIN B. CHAMPAGNE

Laser Technology Branch, Air Force Avionics Laboratory, Wright-Patterson AFB, Ohio 45433

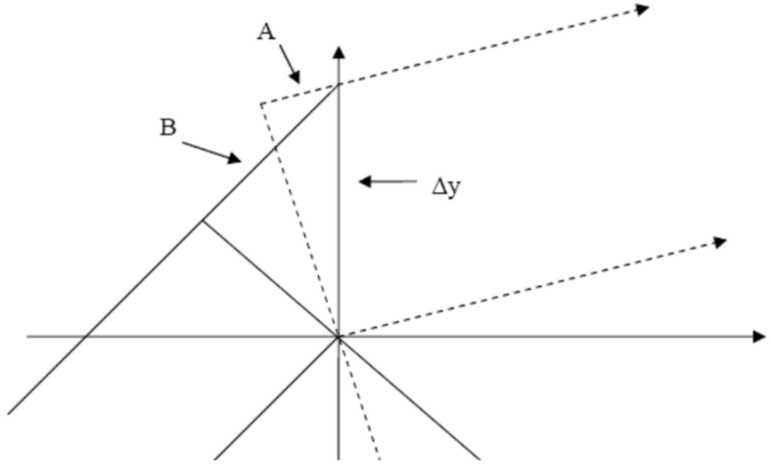
(Received 9 July 1966)

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



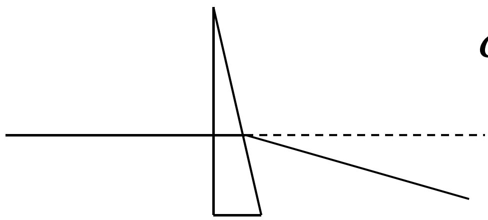
$$n'\sin(I')\cdot\Delta y = n\sin(I)\cdot\Delta y$$

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

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

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

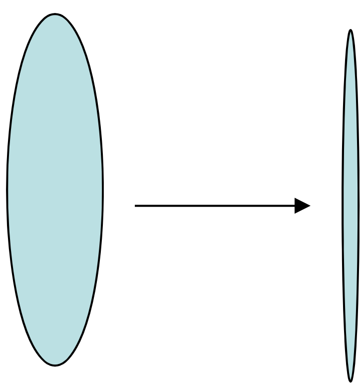
Sweatt's model



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

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

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

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

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

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

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

Sweatt’s Model

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

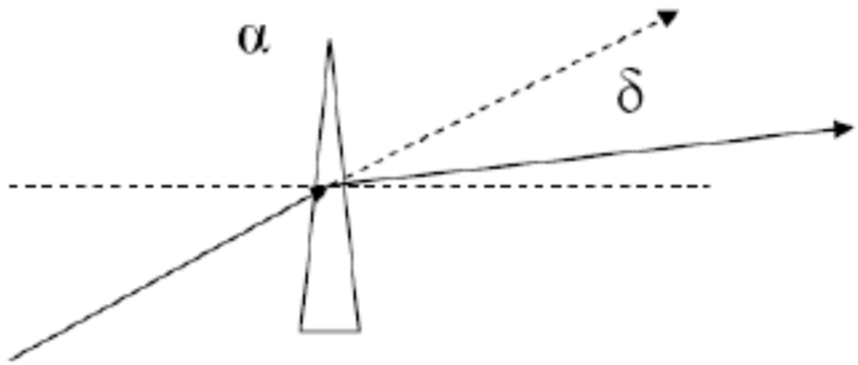
$$\tan(\alpha) = \frac{m\lambda \quad (1/d)}{n'\cos(I') - n\cos(I)}$$

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



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

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

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

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

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Dispersion in Sweatt's model

Consistent with diffraction case

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

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

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

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)

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

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

$$S_{III} = \text{Ж}^2 \varphi$$

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

$$S_V = 0$$

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

$$C_T = 0$$

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

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

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

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

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

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

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

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

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

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	
$\sigma_I = AX^2 - BXY + CY^2 + D$	$A = \frac{n+2}{n(n-1)^2}$
$\sigma_{II} = EX - FY$	$B = \frac{4(n+1)}{n(n-1)}$
$\sigma_{III} = 1$	$C = \frac{3n+2}{n}$
$\sigma_{IV} = \frac{1}{n}$	$D = \frac{n^2}{(n-1)^2}$
$\sigma_V = 0$	$E = \frac{n+1}{n(n-1)}$
$\sigma_L = \frac{1}{\nu}$	$F = \frac{2n+1}{n}$
$\sigma_T = 0$	

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

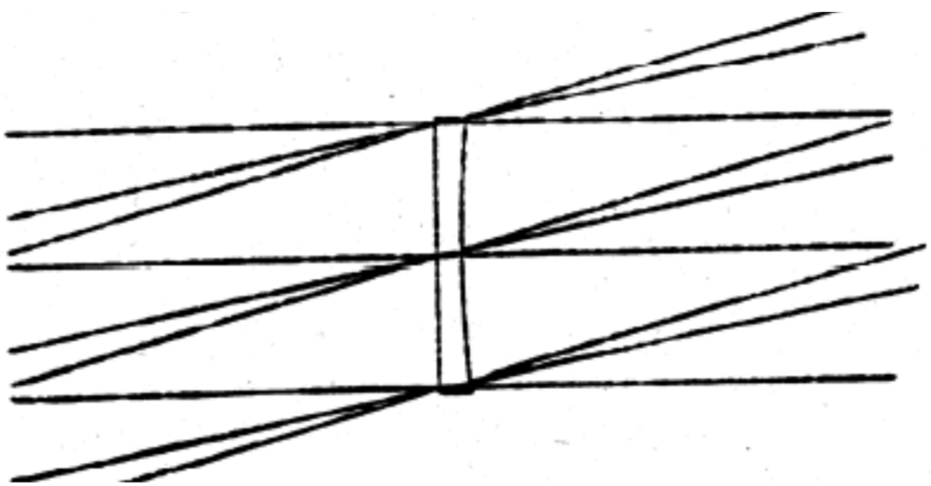
$$\sigma_{II} = \frac{2}{\phi R_2} - 2Y$$

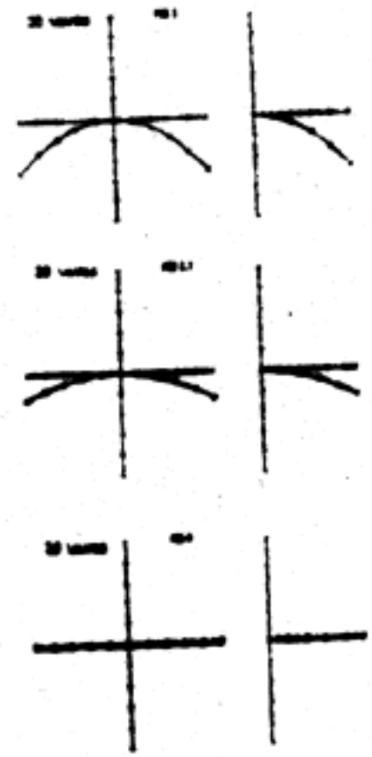
$$\sigma_{IV} = 0 \qquad \sigma_V = 0$$

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

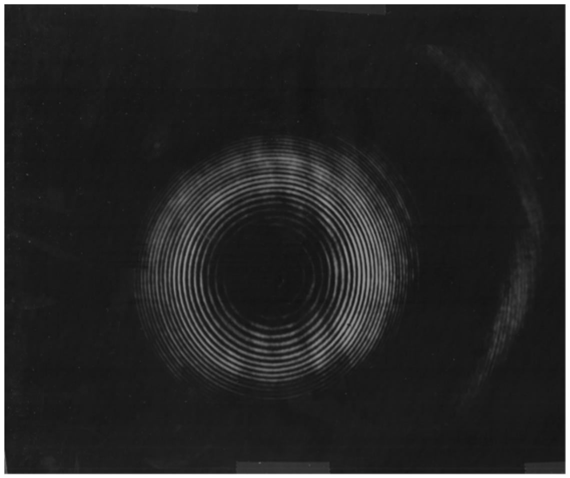
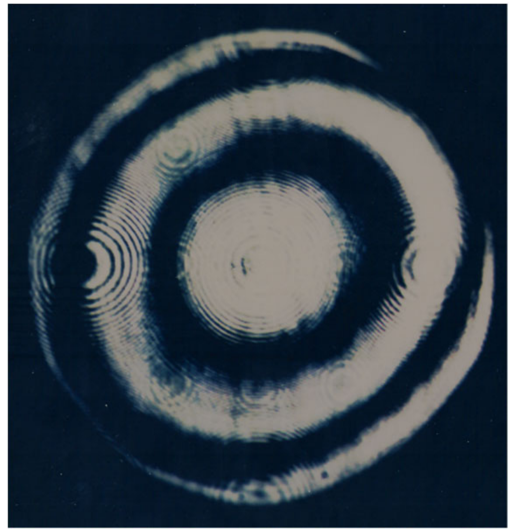
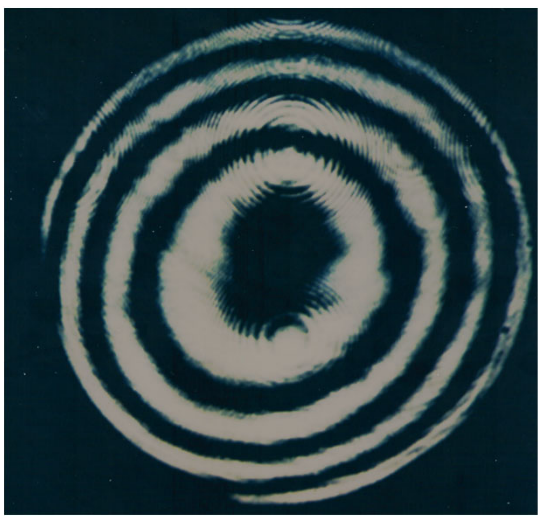
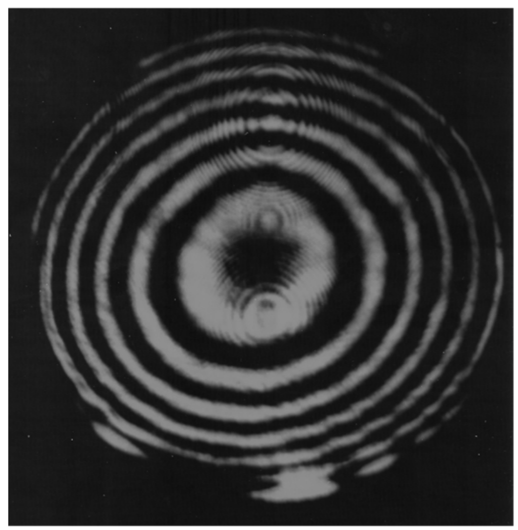
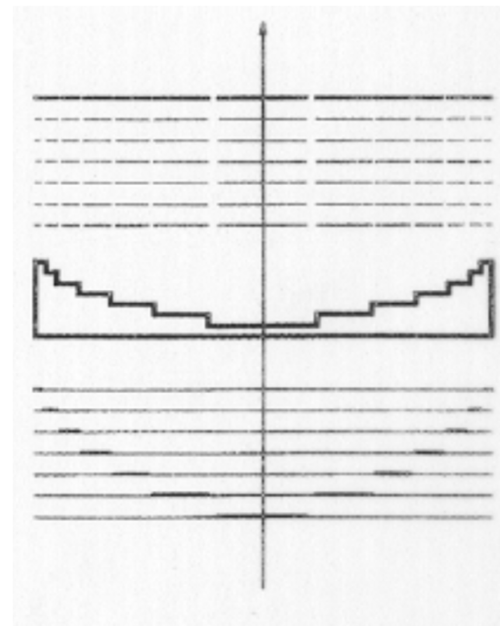
$$\sigma_T = 0 \qquad \sigma_{III} = 1$$

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

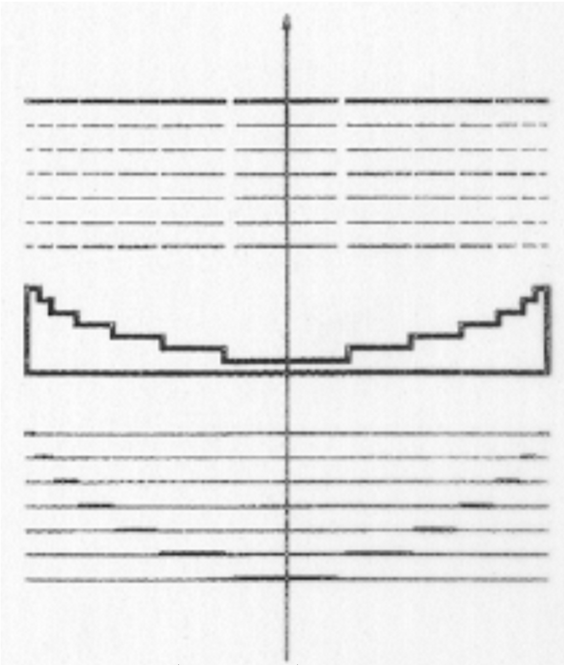
$$OPD_F = \frac{y^2}{2R}\left((n_F - 1) + (n_d - 1)\frac{\lambda_F}{\lambda_d}\right)$$

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

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

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

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



$$OPD = (n-1)\times t + N \times \lambda$$

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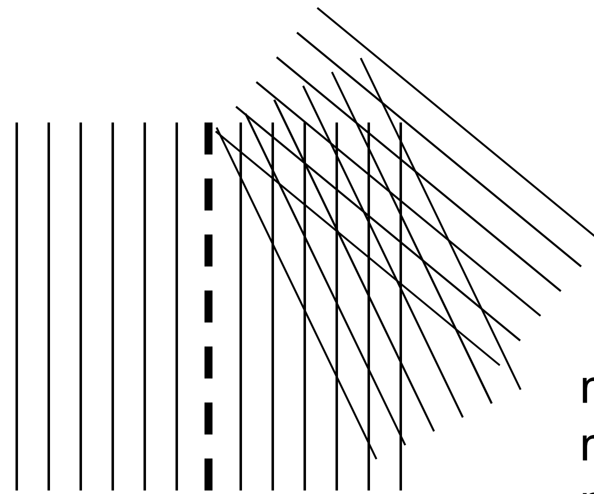
Spherical aberration

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

$$\varphi(\rho)=\frac{2\pi}{\lambda}\cdot\left(a\rho^2+b\rho^4+c\rho^6+d\rho^8+.....\right)$$

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

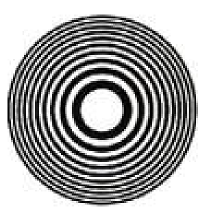
$$F(\nu) \cong \frac{A}{2} SINC\left(\frac{\nu}{2\nu_0}\right) \sum_{-\infty}^{\infty} \partial(\nu - n\nu_0) = \frac{A}{2} \sum_{-\infty}^{\infty} SINC\left(\frac{n}{2}\right) \partial(\nu - n\nu_0)$$

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

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

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

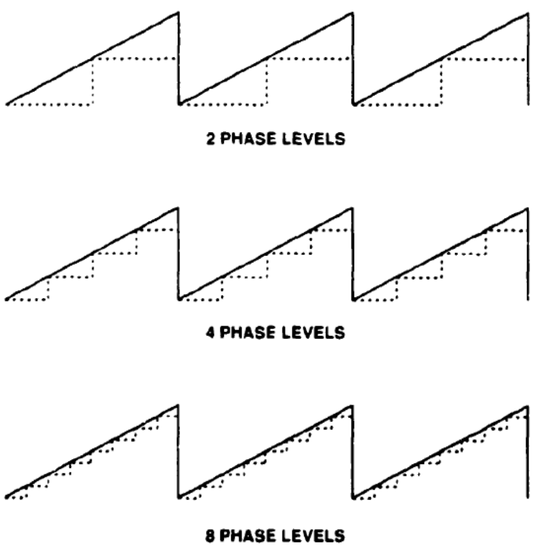
$$\nu_0 = T^{-1}$$

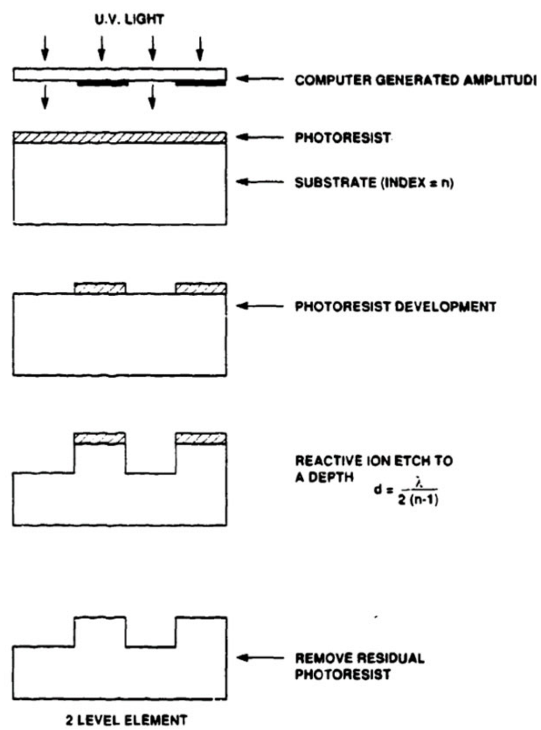


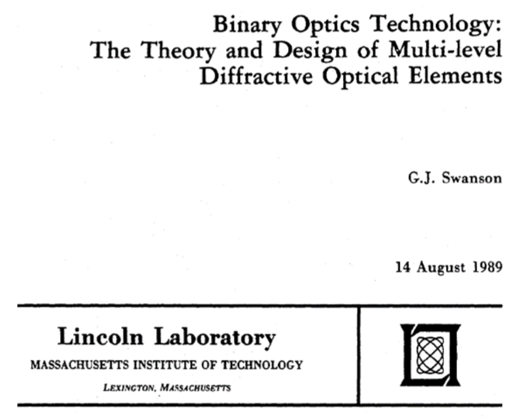
50% duty cycle

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

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

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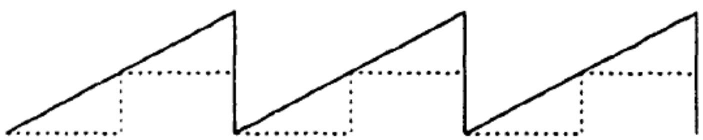
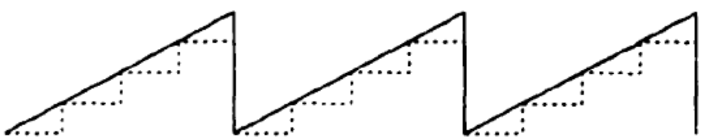
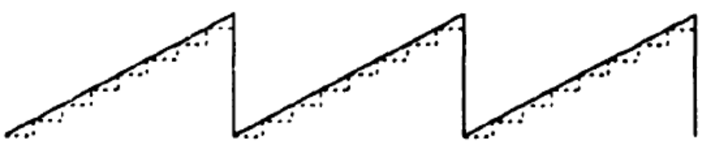
Efficiency for binary optics



2 PHASE LEVELS



4 PHASE LEVELS

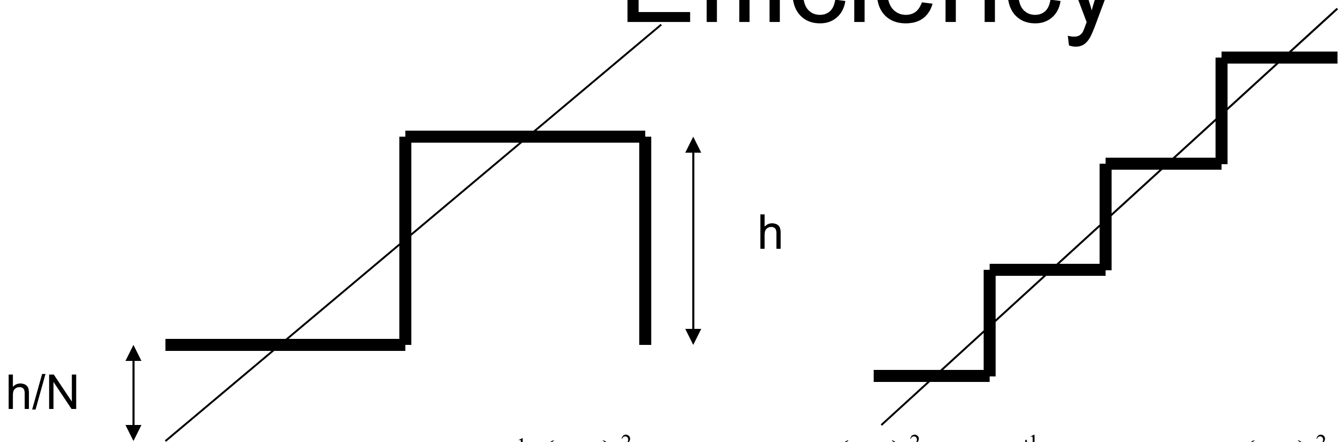


8 PHASE LEVELS

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

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

Efficiency



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

$$h = 1$$

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

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

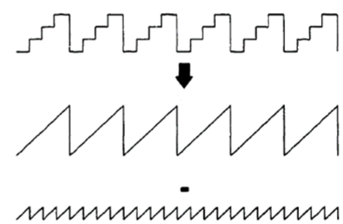
$$S \approx 1 - \frac{\pi^2}{3}\left(\frac{1}{N}\right)^2$$

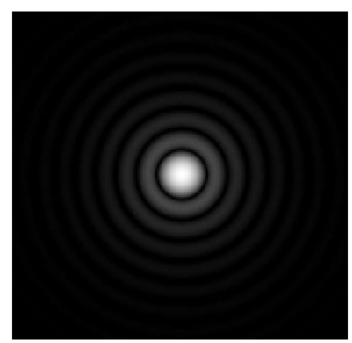
$$N = 2 \;; S = 0.17$$

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

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

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





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

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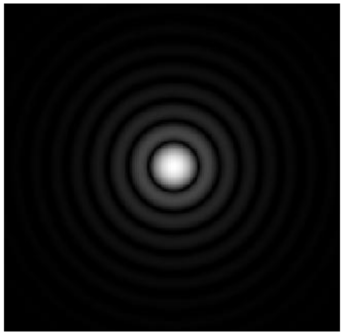
Rayleigh - Strehl ratio with Shack formula



$$RS \approx \exp\left\{-\left(\frac{2\pi}{\lambda}\sigma\right)^{2}\right\} = \exp\left(-\left(\frac{2\pi^{2}}{\lambda}\right)^{2}\left(\frac{1}{12}\lambda^{2}\left(\frac{1}{N}\right)^{2}\right)\right)$$

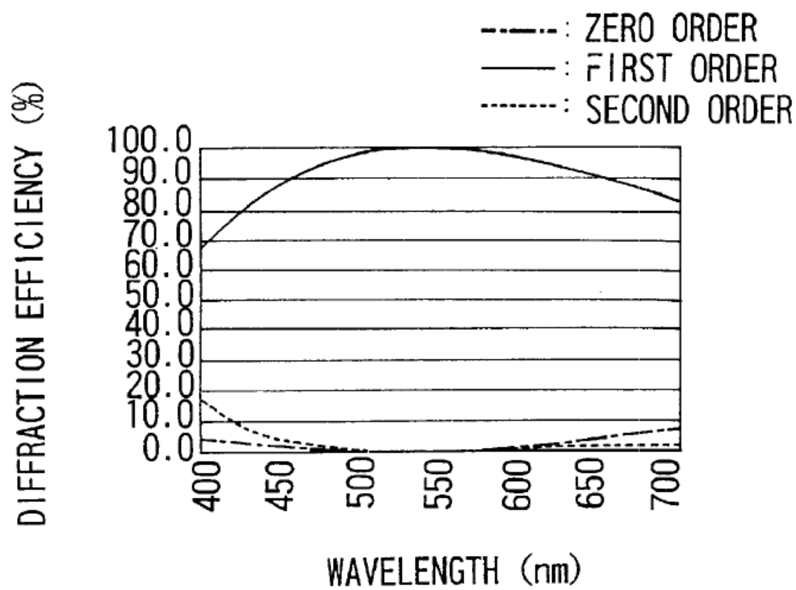
$$= \exp\left(-\frac{1}{3}\left(\frac{\pi}{N}\right)^{2}\right)$$

N=2; RS=0.439
N=4; RS=0.814
N=8; RS=0.949
N=16; RS=0.987

Number of Levels N	First-Order Efficiency $\eta_1{}^N$
2	0 41
3	0.68
4	0.81
5	0.87
6	0.91
8	0.95
12	0.98
16	0.99

Efficiency

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



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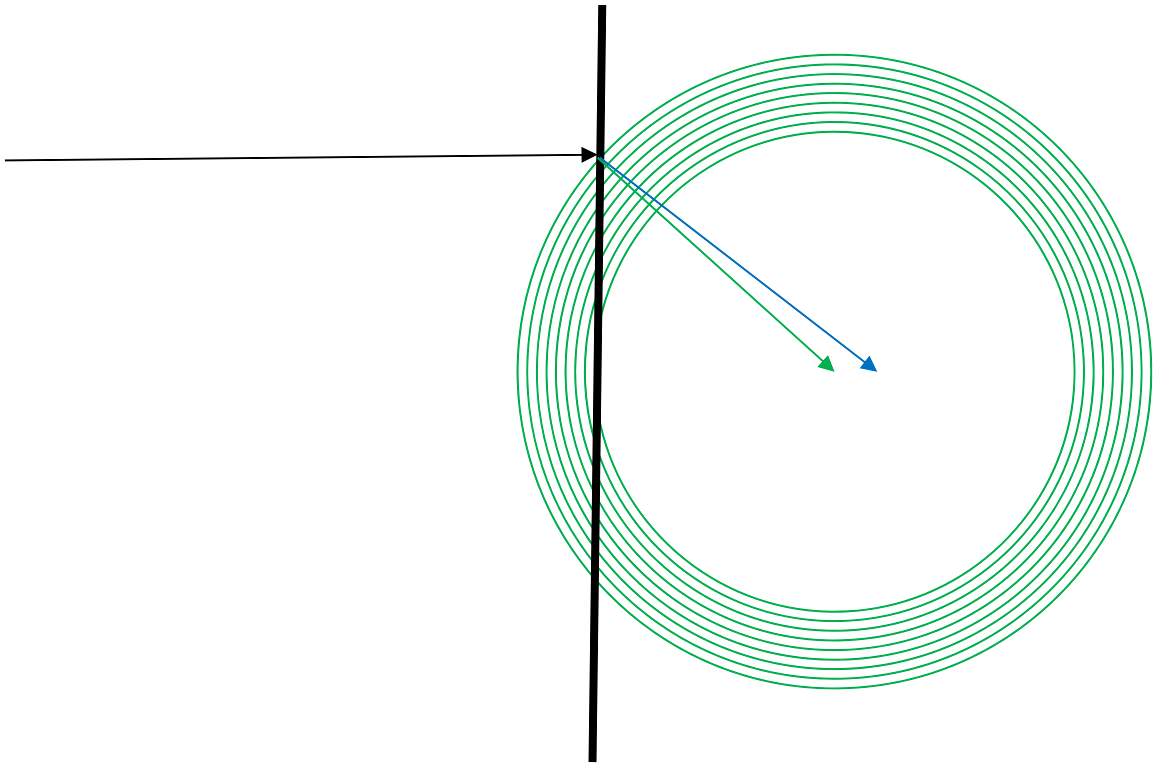
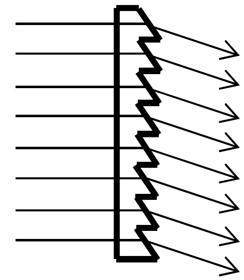
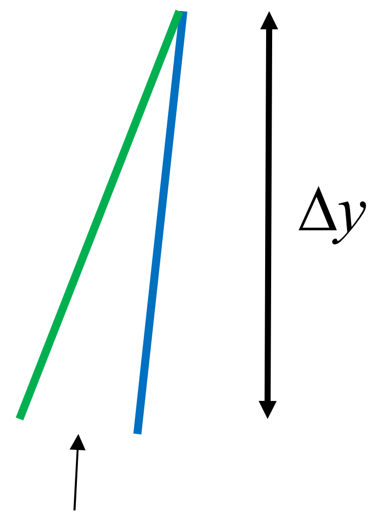
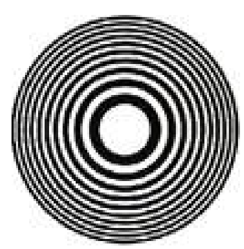
Efficiency









$$OPD \approx \left(\left(n_F - 1 \right) \alpha \Delta y - \left(n_d - 1 \right) \alpha \Delta y \right) - \left(\lambda_F - \lambda_d \right)$$
$$= \left(n_F - n_d \right) t - \left(\lambda_F - \lambda_d \right)$$

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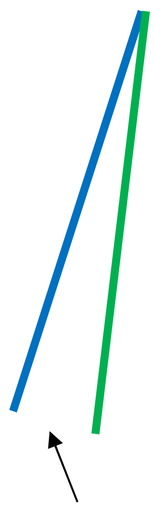
Variance



$$OPD \approx \left((n_F - 1)\alpha\Delta y - (n_d - 1)\alpha\Delta y \right) - (\lambda_F - \lambda_d)$$
$$= (n_F - n_d)t - (\lambda_F - \lambda_d)$$

$$\sigma^2 = \frac{1}{4}\int_{-1}^{1} (hx)^2\, dx = \left(\frac{h}{2}\right)^2 x^3 \frac{1}{3}\Big|_{-1}^{1} = \frac{2}{3}\left(\frac{h}{2}\right)^2 = \frac{1}{6}h^2$$

$$\sigma = \frac{1}{\sqrt{6}}h = \frac{1}{\sqrt{6}}\left((n_F - n_d)t - (\lambda_F - \lambda_d) \right)$$

Efficiency

$$\varepsilon \approx \exp\left\{-\left(\frac{2\pi}{\lambda_F}\sigma\right)^2\right\} = \exp\left\{-\left(\frac{2\pi}{\lambda_d}\frac{\lambda_d}{\lambda_F}\frac{(n_F-n_d)t-(\lambda_F-\lambda_d)}{\sqrt{6}}\right)^2\right\}$$

$$= \exp\left\{-\left(\frac{2\pi}{\sqrt{6}}\left(\frac{\lambda_d}{\lambda_F}\frac{n_F-n_d}{n_d-1}-\frac{\lambda_F-\lambda_d}{\lambda_F}\right)\right)^2\right\}$$

$$(n_d-1)t=\lambda_d$$

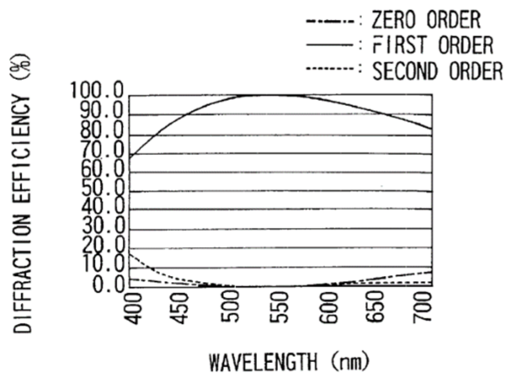
$\frac{2\pi}{\sqrt{6}}$

λ	n	ε
0.4000	1.5308	0.3354
0.4300	1.5273	0.5520
0.4600	1.5244	0.7498
0.4900	1.5221	0.8945
0.5200	1.5202	0.9758
0.5500	1.5185	1.0000
0.5800	1.5171	0.9809
0.6100	1.5159	0.9328
0.6400	1.5148	0.8682
0.6700	1.5139	0.7959
0.7000	1.5131	0.7223

$\frac{2\pi}{4}$

λ	n	ε
0.4000	1.5308	0.6635
0.4300	1.5273	0.8000
0.4600	1.5244	0.8975
0.4900	1.5221	0.9590
0.5200	1.5202	0.9908
0.5500	1.5185	1.0000
0.5800	1.5171	0.9928
0.6100	1.5159	0.9742
0.6400	1.5148	0.9483
0.6700	1.5139	0.9179
0.7000	1.5131	0.8850

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



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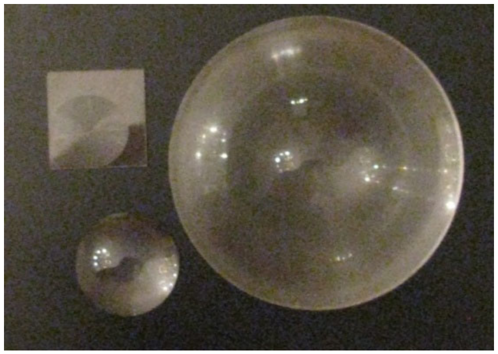
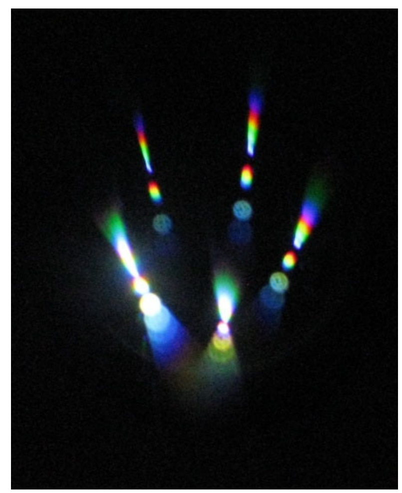
Comparison

Standard lens, Fresnel lens and DOE lens



Refracting lens

Fresnel lens



DOE lens

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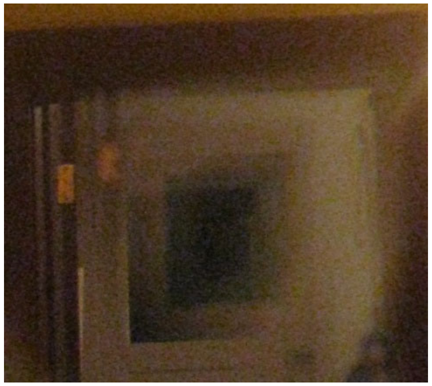
Images of extended objects



Acrylic powerless lens

Other orders produce images at different magnifications
Like ghost images

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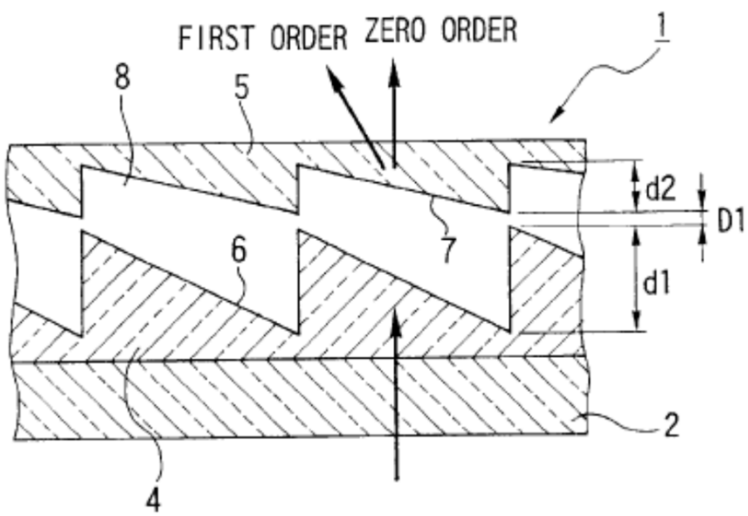
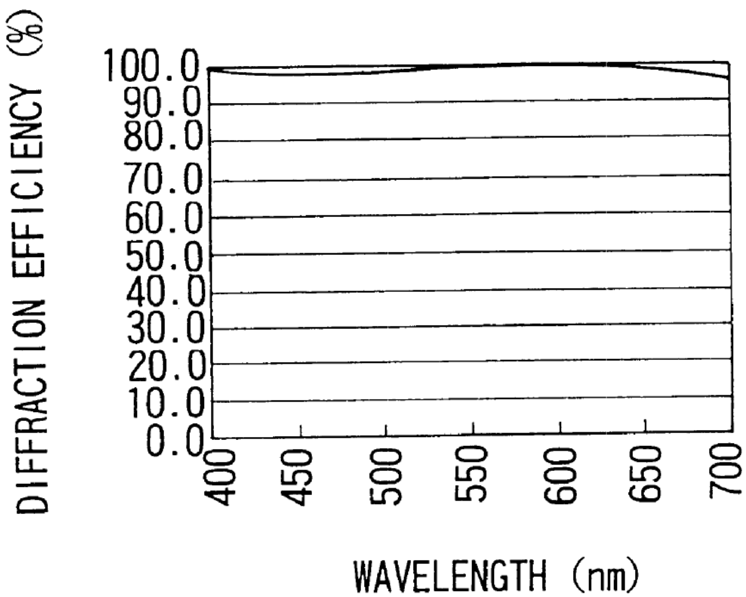
Canon's multilayer DOE's





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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**

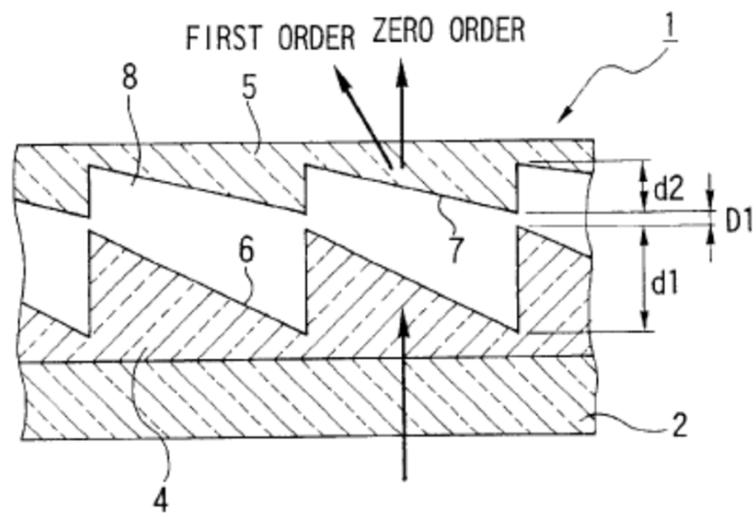
(54) **DIFFRACTIVE OPTICAL ELEMENT AND PHOTOGRAPHIC OPTICAL SYSTEM HAVING THE SAME**

(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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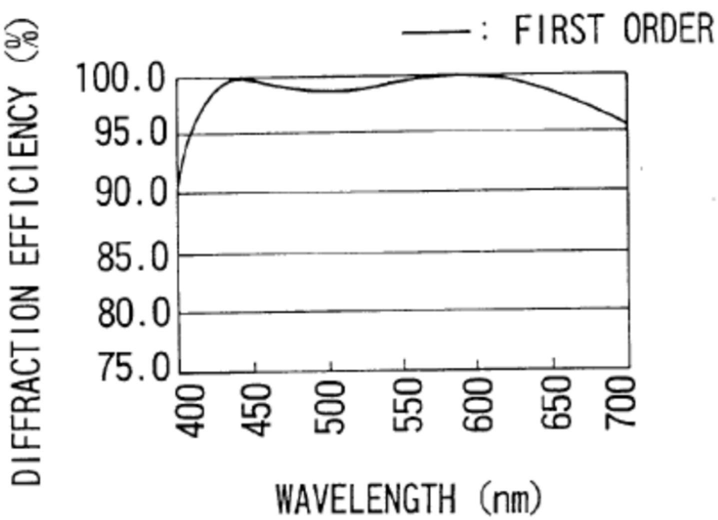
How does it work?

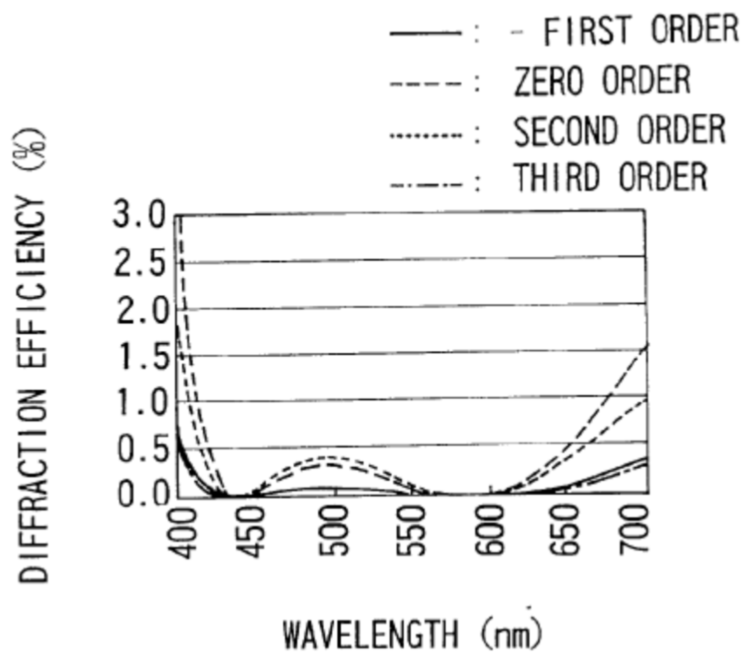
$$\varepsilon(\lambda)=\sin c^2\left(\pi\left[\frac{\lambda_{construction}}{\lambda_{reconstruction}}\frac{n(\lambda_{reconstruction})-1}{n(\lambda_{construction})-1}-m\right]\right)$$

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

$$\varepsilon(\lambda)=\sin c^2\left(\pi\left[d_2\,\frac{n_2(\lambda_{reconstruction2})-1}{\lambda_{reconstruction2}}\pm d_1\,\frac{n_1(\lambda_{reconstruction1})-1}{\lambda_{reconstruction1}}-m\right]\right)$$

100% at two wavelengths





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Canon lens

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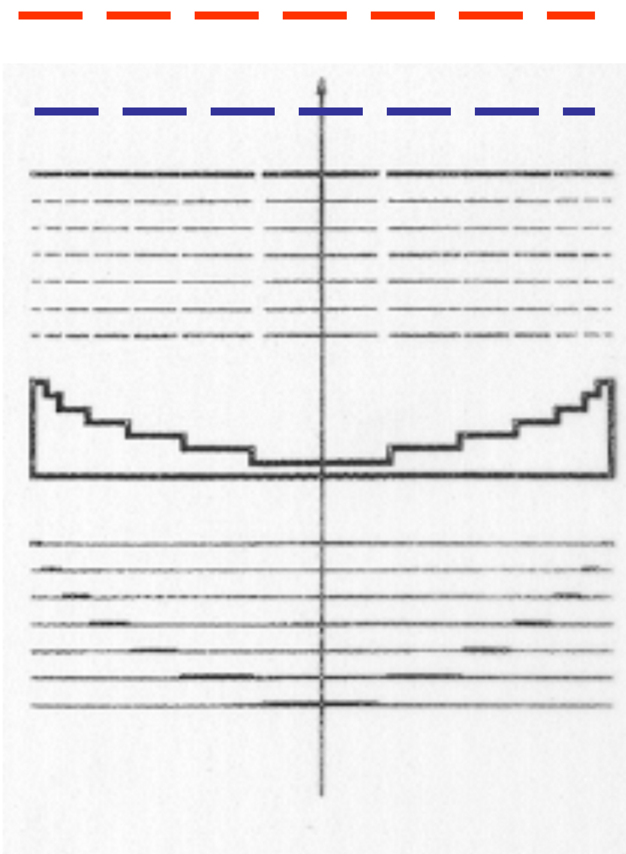
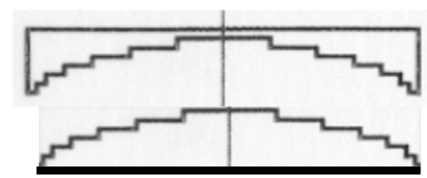
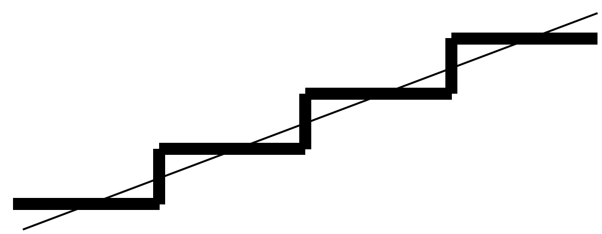
Alternate view
100% efficiency at 2λ (no ripple)

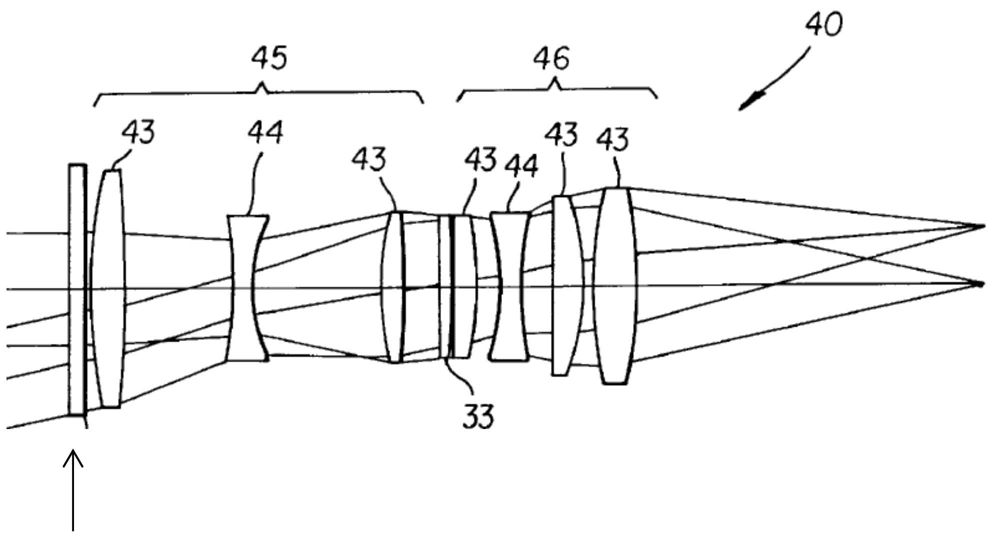


$$\lambda_2 = 2\lambda_1 = 2(450nm)$$





An actual lens application for controlling chromatic change of magnification



DOE

(12) **United States Patent**
Harrigan

(54) **MOVIE PROJECTION LENS**

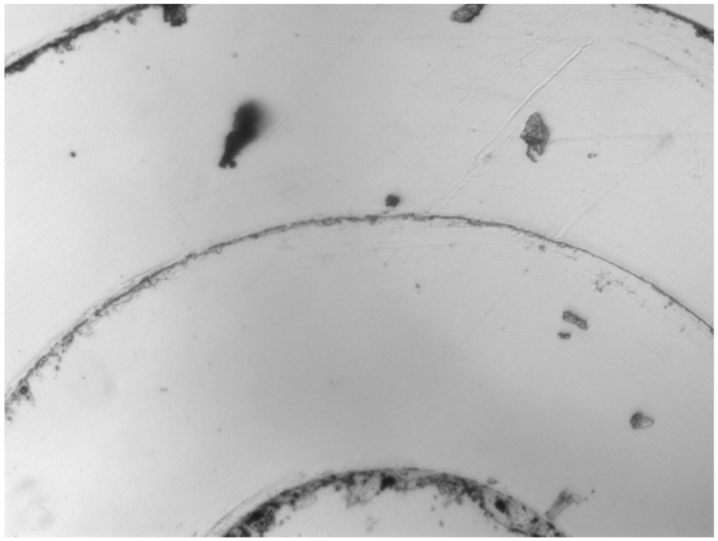
(75) Inventor: **Michael Harrigan**, Webster, NY (US)

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

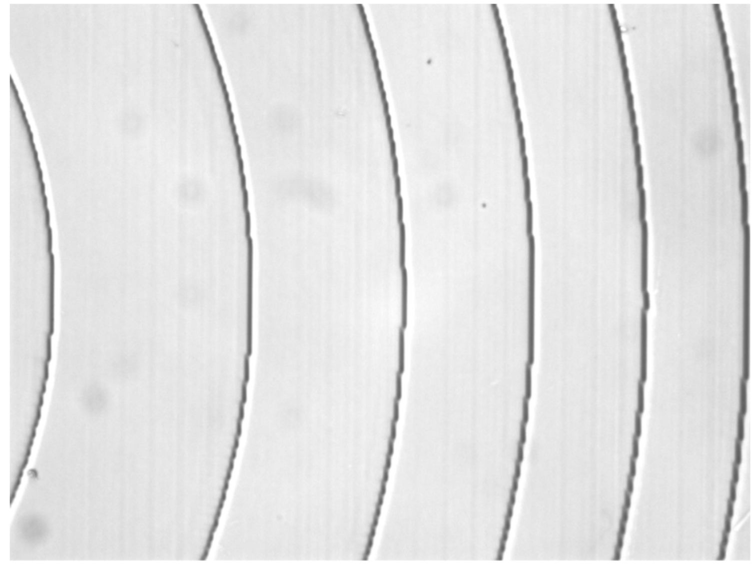
(10) **Patent No.: US 6,317,268 B1**
(45) **Date of Patent: Nov. 13, 2001**

Note lack of lens symmetry about the stop

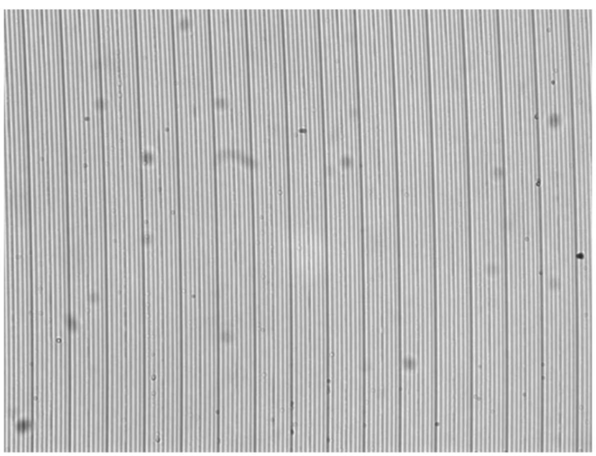
Some Fresnel lens and DOE photographs



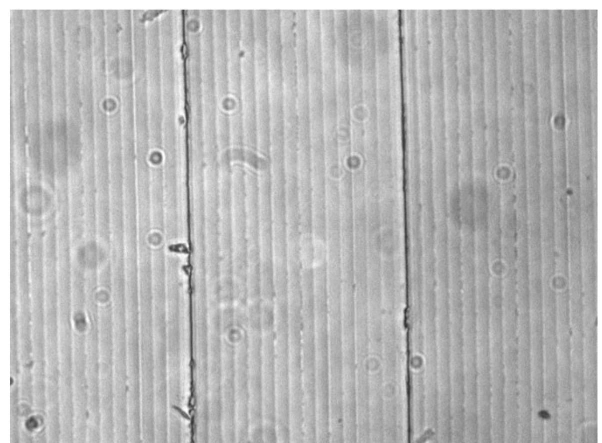
Plastic Fresnel lens;
Diamond turned and replicated



Gray scale; note binary edge

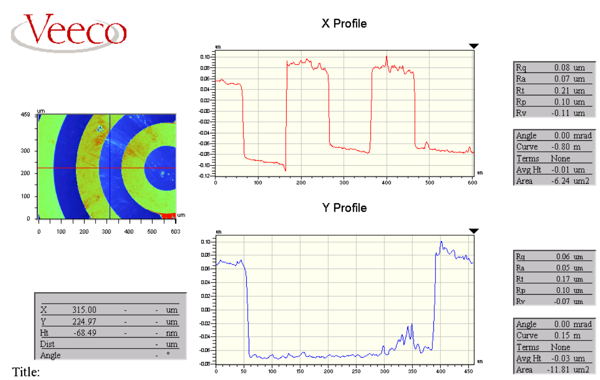


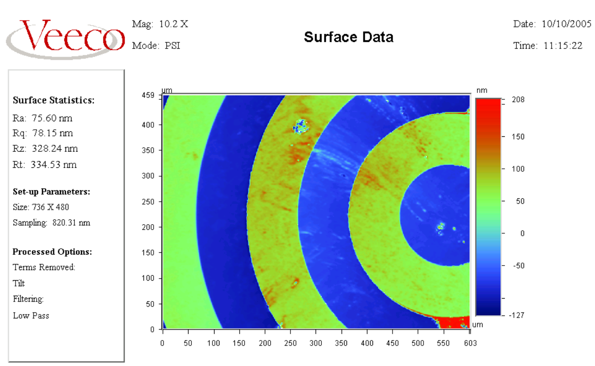
Binary 8 levels



Binary 16 levels

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

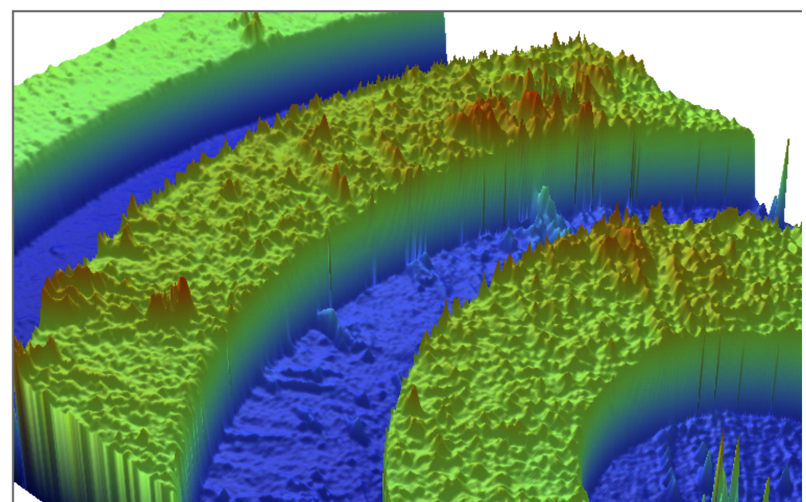
Measurement Info:

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