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MANUFACTURING THE KEY TO BINARY OPTICS

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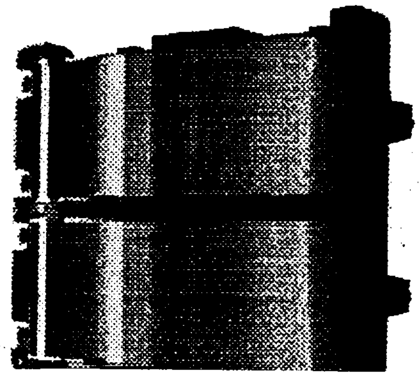
Gratings

1786	First Grating David Rittenhouse	
1821	Spectroscopy Joseph Fraunhofer	
1882	Concave Grating H.A. Rowland	
1910	Blazed Grating R.W. Wood	



- American astronomer, David Rittenhouse, noticed diffraction from silk handkerchief and invented diffraction grating in 1786. He made no scientific measurements but did note red was bent more than blue.
- Joseph von Fraunhofer independently invented the diffraction grating in 1821 and used it to look at the sun's spectrum. He derived and verified the grating equation. He examined the effects of groove shape and position.
- In 1822 Sir John Barton, deputy controller of the London Mint patented the use of gratings in ornaments such as waistcoat buttons. This was the first commercial application of diffractive optics!
- H.A. Rowland of Johns Hopkins University invented concave gratings which allowed the spectrum to be focused into a sharp image. This enabled spectroscopy to extend into u.v. It enhanced accuracy of relative wavelength measurements.
- R.W. Wood developed a technique for controlling the distribution of light among the diffracted orders by controlling the shape of the grooves – **blazing**.

Grating Characteristics

- Fourier transform of grating structure displayed as angular spectrum
- Spectral sensitivity is an advantage
- No power
- Higher orders *"passed off"* (diffracted beyond 90°)
- Hard edges lead to many orders

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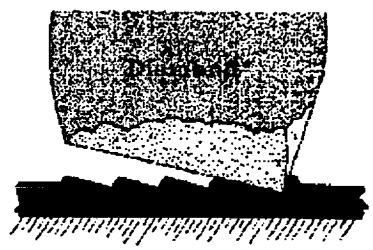
- The spatial Fourier transform of the grating structure gives an angular spectrum. Because the ruled grating has hard edges, there are many high orders.
- Only a finite number of orders are observable because once the diffraction angle has reached 90° no orders are observable. The orders are said to be "passed off".
- The grating period is a constant thus the grating has no power. To focus light, the grating surface must be curved.
- For this optical component, dispersion is an advantage.

Grating Construction ☛

Grating Manufacture

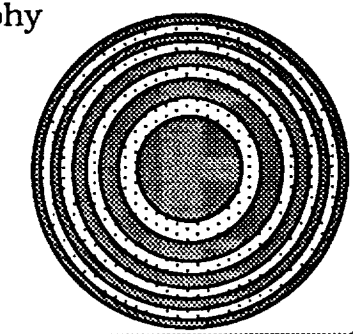
- First observations with silk handkerchief
- First grating used hair to create apertures
- H.A. Rowland made first ruling engine
- R.W. Wood developed diamond tool for blazing
- Replication developed by J.V. White & W.A. Fraser



- The first grating was a fine silk handkerchief but in order to produce a more controlled condition, Rittenhouse made a grating of hairs spaced by two screws.
- Fraunhofer made his first transmission grating using wires held in screw threads and his first reflection grating by ruling grooves with a diamond point on a mirror surface. His best effort was a 12 mm wide grating with 9600 grooves.
- Rowland built a ruling engine in 1882 which was not the first but was the first **successful** device.
- John Hopkins University produced most of the accomplishments in grating technology up to the Second World War
  Wood developed blazed gratings
  Strong introduced the use of vacuum deposition of thin metal films for ruling.
- In **1915** Michelson suggested that the ruling engine be controlled by an interferometer and in **1955** the first use of an interferometer was made by Stroke of Johns Hopkins.
- Probably the most important development other than the ruling engine was the development by White and Fraser in 1949 of high quality replication.

Zone Plate

1871	First zone plate Lord Rayleigh
1898	Phase Zones R.W. Wood
1950	Connection to holography G.L. Rogers
1961	Application to x-rays A. Baez



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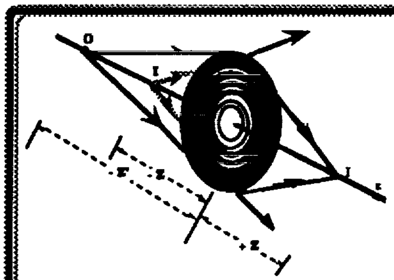
- The first zone plate with 15 zones was drawn by hand in 1871 by Lord Rayleigh.
- Lord Rayleigh suggested construction of a phase zone plate which was made by R.W.Wood in 1898.
- The connection between zone plates and holography brought a renewed interest in these optical elements.
- Ac curiosity until the ability to make zone plates using microlithography allowed the application of zone plates to x-ray optics. It is here that zone plates have found a real niche since there is little competition.
- The reason zone plates are seldom used can be found by examining their attributes.

Zone Plate Characteristics



- Chirped grating with power
- Chromatic effects is handicap
- Resolution determined by grating period
- Fourier transform of grating structure displayed along optical axis
- All orders are observable yielding large amount of stray light

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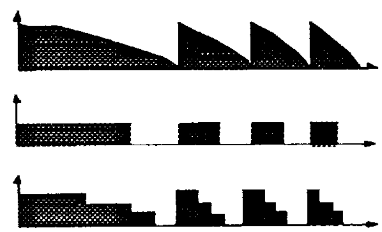
- The zone plate is made of concentric rings. The area of each of the rings is the same. The radii of the rings are proportional to the square root of the natural numbers.
- This construction results in a radial chirped grating. This gives the zone plate power allowing it to be used as a lens.
- The Fourier transform of this chirped grating is displayed along the optical axis of the zone plate. This distribution is viewed as foci of the zone plate.
- Because of the hard edges of the zone grating, an infinite number of foci appear along the optical axis. This leads to a lot of stray light.
- At best the zone plate will produce only a real and a virtual image.
- The dispersion of the zone plate is a handicap.

Zone Plate Manufacture

- Originally hand drawn
- Photographic reduction
- Ruling machine first used near turn of the Century
- Electron beam writing
- Blazed zone plates



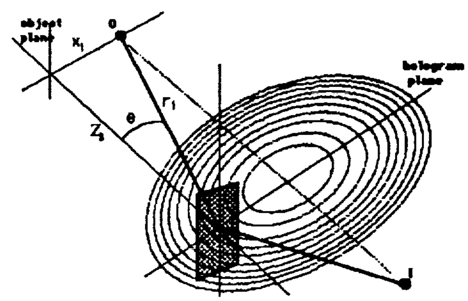
- Lord Rayleigh, in 1871, drew by hand the first zone plate which contained 15 zones alternately blackened.
- It was obvious to Rayleigh that the zone plate could be improved by replacing the darkened zones by transparent zones that simply reversed the phase. This was first done in 1898 by Robert Wood.
- Wood also developed a rotary ruling machine that allowed zone plates to be machined. He first used a wax substrate and a record needle.
- The microelectronic industry developed a number of techniques that allowed zone plates for the x-ray region to be produced.
- Photographic techniques have even been used to produce blazed zone plates with enhanced diffraction efficiency.

Holography

1927 A.A. Michelson suggested interferometry to make gratings

1949 Dennis Gabor invented holography

1962 E.N. Leith & J. Upatnïeks invented off axis holography



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- In 1948 Dennis Gabor invented holography as a means of increasing the resolution of electron microscopy.
- The first suggestion of recording interference fringes to produce a diffractive optical component was by Michelson in 1927.
- The first gratings were made by J.M. Burch in 1960.
- Gabor's idea was not practical until the invention of the laser and the concept of off axis holography developed by Leith and Upatnieks in 1962.
- The view of the hologram as a segment of a zone plate was first suggested by Gabor and developed by G.L. Rogers in 1952.
- The zone plate analogy is a useful way of understanding the imaging properties of holography.

Holographic Aberration Correction

J. Upatnieks, A. Vander Lugt, and E. Leith "Correction of lens aberrations by means of holograms," *Applied Optics*, **5**, 589-593 , (1966)

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- Even with all the difficulties, optical components have been produced.
- The first optical components as well as the first aberration correction of refractive components was done in 1966.
- Here a **before** photo is shown with a large amount of spherical aberration.
- The **after** photo demonstrates the removal of the spherical aberration by the use of a hologram.

Wavefront Generated Holograms

Advantages

- Sinusodial gratings
- Curved grooves
- Curved substrate
- Dynamic components with photorefractives

Problems

- Wavefront generation
- Control of groove shape and depth
- Materials

  Stability during and after processing
  Spectral and intensity sensitivity

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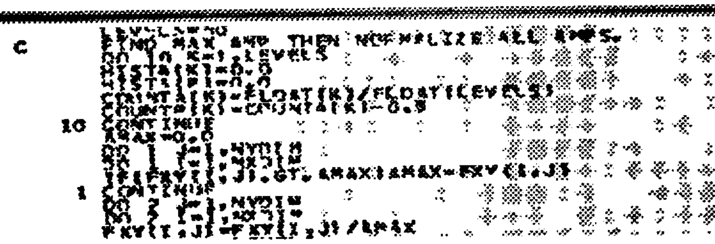
- Holography allows sinusoidal grooves to be produced, eliminating higher orders in amplitude recordings.
- With photorefractive materials it is possible to consider dynamic diffractive elements.
- The substrate can have any shape.
- To generate a desired groove profile optically, Fourier synthesis techniques have been used. Here, in theory, a number of sinusoidal exposures are superimposed to generate the desired shape.
- Groove shape and depth has been very difficult to control.
- It is often hard to generate the desired wavefront so we have turned to the computer.

Computer Generated Hologram



1966 Detour phase technique
A.W. Lohman

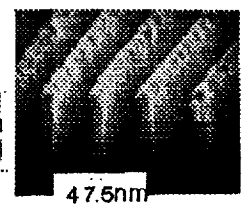
1969 Kinoform
L.B. Lesem

- Driven by the need to produce arbitrary waveforms. Computer generated holography was developed.
- The first CGH were produced using one bit computer plotters. The results of such a plotter are shown in the montage on this viewgraph.
- Kinoforms are computer generated holograms that modulate only the phase. This is done by using a gray scale film recorder. The master is reduced and bleached to convert the gray scale to optical path modulation.
- New fabrication technologies have been developed that provide seemly unlimited capability.

Fabrication

- **Diamond Turning**
- **Optical Recorders**
  - Dichromatic gelatin
  - Photoresist
  - Photopolymer
- **Electron Beam Recorders**
  - Wet etching
  - Plasma etching
  - Ion beam milling
  - Ion exchange
  - Implantation
  - Lift off

380 nm



- Diamond turning utilizes the same technique as the grating ruling machines.
- Optical techniques use interferometry, beam writing, or imaging
- Dichromate provides 3000 l/mm resolution, low noise and high index modulation but it is sensitive to humidity. Dichromate undergoes shrinkage and swelling during processing.
- Photoresist has high resolution, 4000 l/mm but is most sensitive to uv. In visible, exposure can take minutes to hours.
- Photopolymers from Polaroid and DuPont have high index modulation (similar to dichromate). Volume changes are small.
- Electron beam lithography uses mask makers from microelectronics. The basic features are trapezoids which lead to errors in binary optics.
- Plasma etching yields 2500 l/mm but has high cost and takes hours.
- Anisotropic wet etching of silicon imposes restrictions on pattern size, groove curvature, spatial frequency variation, and reproducibility.
- Ion beam milling is slow and non-selective making it not useful to microelectronics but its properties are great for diffractive optics.
- Implantation, diffusion and ion exchange produces imbedded diffractive structures.

Fabrication Capabilities

	Machine	Feature Size μm	Space Bandwidth	Accuracy μm	Speed Pixel/sec
Single Beam Optical	Galvanometer	5	4×10^6	1	10^3
	Rotating Drum	5	1.6×10^7	1	10^4
	Translaton	1	10^{10}	0.5	10^6
	Rotating Disk	1	10^{10}	0.5	10^6
Parallel Optical	Imaging	5	10^8	1	10^4
	Interference	1	10^8	1	10^3
Electron Beam	Mask Maker	0.2	10^{10}	0.1	10^5
	Microscope	0.5	10^8	0.1	10^6
Mechanical	Lathe	0.2	10^{10}	0.1	10^6
	Milling	0.2	10^{10}	0.1	10^6

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- Here are resolutions obtained from various commercial writing systems.
- Optical systems all have resolutions around 1 μm while electron beam has 0.2 μm.
- Optical systems can produce gray scale while electron beam devices cannot.
- Pattern generators designed for the microelectronics industry have problems currently with circularly symmetric patterns. They want to produce trapezoids all oriented in the same way.
- The use of patch by patch construction using interferometry has not been successfull.
- Major problem is all writing techniques are serial! These devices can produce masters but we need to be able to replicate to lower cost and increase speed of production.

Replication

- **Casting**
  Can be done with high accuracy
  Slow
- **Embossing**
  Hard to obtain high resolution
  Poor dimensional stability
- **Photocopy**
  Reproducibility problems
- **Injection molding**

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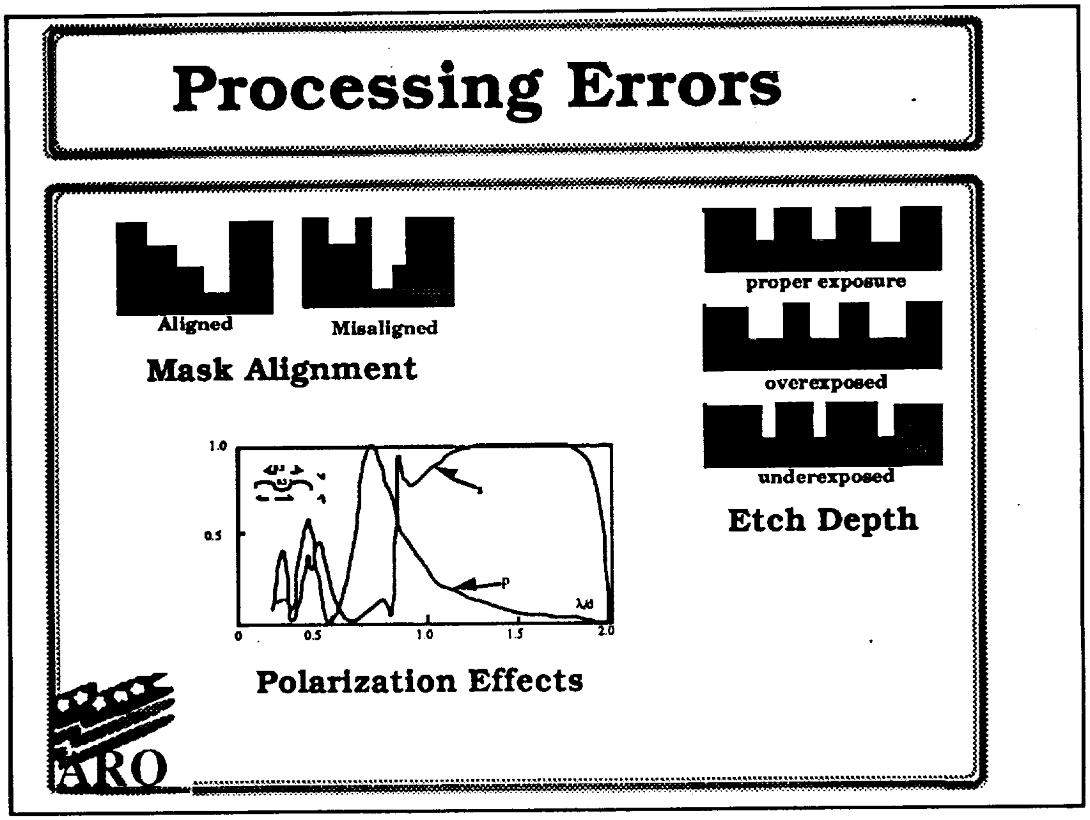
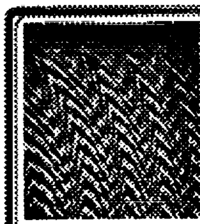
- Lord Rayleigh demonstrated at the turn of the century replication was possible by casting but it was not practical until 1949.
- A good release was needed so that the master was not destroyed during the replication process.
- The key to the wide spread use of gratings has been the development of replicating techniques and it will also be true for diffractive optics.
- If we are to use diffractive optics in transmission the substrate must be of good optical quality. This is not necessary in grating production.
- Casting using epoxy or sol gel can be done with extreme accuracy but it is slow.
- It is difficult to emboss extremely small diffractive structures and the plastics that are used in embossing have poor environmental stability.
- Holographic recording or copying is not very reproducible. It is hard to control the chemistry.
- Injection molding has been very successful for camera lenses but I am unaware of its use in diffractive optics.



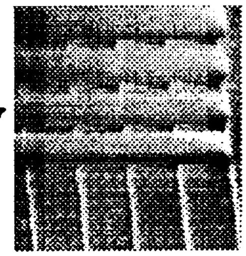
- Groove placement errors result in near scatter noise such as ghost and grass.
- Far scatter effects result from groove shape errors.
- The diffraction efficiency is very sensitive to groove shape. Ridge widths less than 0.01 of the minimum zone width are required.
- Image quality is not sensitive to groove shape and depth but noise due to scatter is.
- Sources of errors are control of development, mask alignment and material shrinkage.
- Polarization effects from processing errors that destroy circular symetry create form birefringence. This is theoretically understood but most lens designers encounter this type of birefringence only with improperly mounted components.

Quality Control



Interferometry

Separation of bulk from grating effects



Scanning Electron Microscopy

Groove shape and depth

Tunneling Microscopy

Optical and dimensional properties

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- In quality control we must be able to separate out the effects of the substrate from the diffractive elements so if there is a problem we can correct the offending element. It may require some intelligent application of interferometry to separate out the two contributions.
- Optical and mechanical methods for measuring groove profiles have resolution limitations. Scanning electron microscopes can be used but the techniques are invasive.
- Tunneling microscopes will provide noncontacting three dimensional measurements of the sample surface.
- Optical tunneling microscopes provide much more than simple groove profiles. By using Raman scattering, we can map out underlying stress fields.

Conclusions

- Theory is in good shape
- Tools for fabrication exist
- Replication needed for manufacturing
- Quality control needs development

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- The theory has been developed since the mid 19 century and is in good shape.
- A wide range of fabrication tools exist. Many need to be modified to optomize for diffractive optics.
- If this technology is to find wide useage, replication must be developed.
- Quality control tools must also be developed.
- Neither of lthe needed developements appear to be unatainable. I expect to see diffractive loptics to become a widely used tool in optics systems design.