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College of Optical Sciences

8.0 Testing Curved Surfaces and/or Lenses

8.0 Testing Curved Surfaces and/or Lenses - I

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  - 8.1.1 Spherometer
  - 8.1.2 Autostigmatic Measurement
  - 8.1.3 Newton's Rings
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8.0 Testing Curved Surfaces and/or Lenses - II

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8.1 Radius of Curvature

There are three common ways of measuring radius of curvature of a surface.

8.1.1 Spherometer
8.1.2 Autostigmatic Measurement
8.1.3 Newton's Rings

8.1.1 Spherometer

A spherometer measures the sag of a surface with great precision. A common spherometer is the Aldis spherometer in which three small balls are arranged to form an equilateral triangle. In the center of the triangle there is a probe mounted on a micrometer.

In use, the surface to be measured is placed on the balls, and the probe is brought into contact with the surface. The sag of the surface is measured using a micrometer. Electronic digital output is common.

Calculating Curvature from Sag

If we denote the sag of the surface by h, the distance between the center of the balls d, and the radii of the balls by r, then the radius of curvature of the unknown surface is given by

$$R = \frac{d^2}{6h} + \frac{h}{2} \pm r,$$

Where the positive sign is taken when the unknown surface is concave, and the negative sign when convex.

If the balls are arranged to form a triangle of sides d_1, d_2, and d_3, the radius of curvature is given by

$$R = \frac{\left(d_1 + d_2 + d_3\right)^2}{54h} + \frac{h}{2} \pm r.$$

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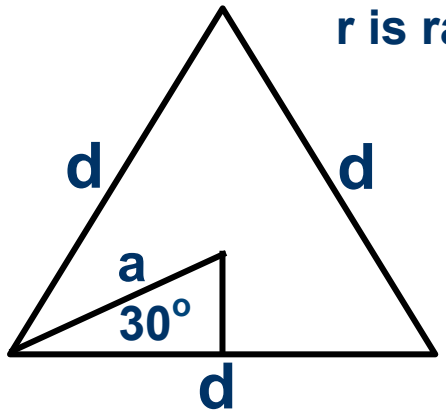
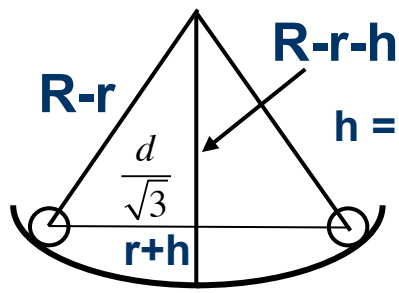
Derivation of Radius of Curvature

R is radius of curvature of surface being measured
r is radius of ball





h = 0 for flat surface

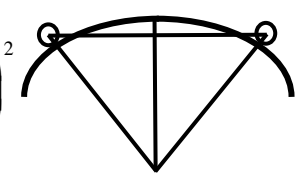
$$Cos\left[30^o\right] = \frac{d/2}{a} \qquad \text{Therefore, } a = \frac{d/2}{Cos\left[30^o\right]} = \frac{d/2}{\sqrt{3}/2} = \frac{d}{\sqrt{3}}$$

$$(R-r)^2 = (R-r-h)^2 + \left(\frac{d}{\sqrt{3}}\right)^2 \qquad (R-r)^2 = (R-r)^2 - 2h(R-r) + h^2 + \left(\frac{d}{\sqrt{3}}\right)^2$$

$$\mathrm{R} = \frac{d^2}{6h} + \frac{h}{2} + r \text{ if concave} \quad \text{or} \quad \mathrm{R} = \frac{d^2}{6h} + \frac{h}{2} - r \text{ if convex}$$

Convex surface

$$(R+r)^2 = (R+r-h)^2 + \left(\frac{d}{\sqrt{3}}\right)^2$$



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Ring Spherometer

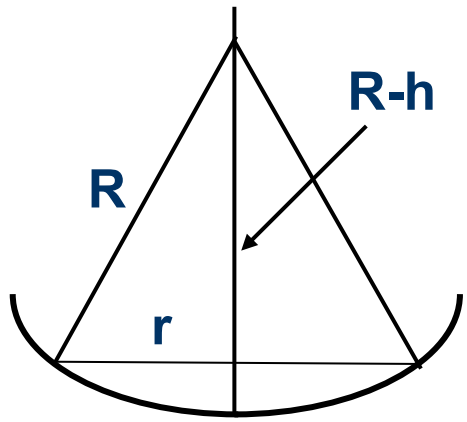
- If a ring spherometer of radius r is used, the radius of curvature is given by

$$R = \frac{r^2}{2h} + \frac{h}{2}.$$

- The major source of inaccuracy in using a spherometer is determining the exact point of contact between the probe and the surface being tested.
- In some spherometers the point of contact is determined by observing the Newton's ring interference pattern formed between the test surface and an optical surface mounted on the end of the probe. As the probe is brought up to the surface, the ring pattern expands, but when the point of contact is reached, no further motion occurs.

Derivation of Radius of Curvature for Ring Spherometer

For ring spherometer of radius r



$$R^2 = r^2 + (R-h)^2 \qquad R^2 = r^2 + R^2 - 2hR + h^2$$

$$\mathrm{R} = \frac{r^2}{2h} + \frac{h^2}{2h}$$

$$R = \frac{r^2}{2h} + \frac{h}{2}$$

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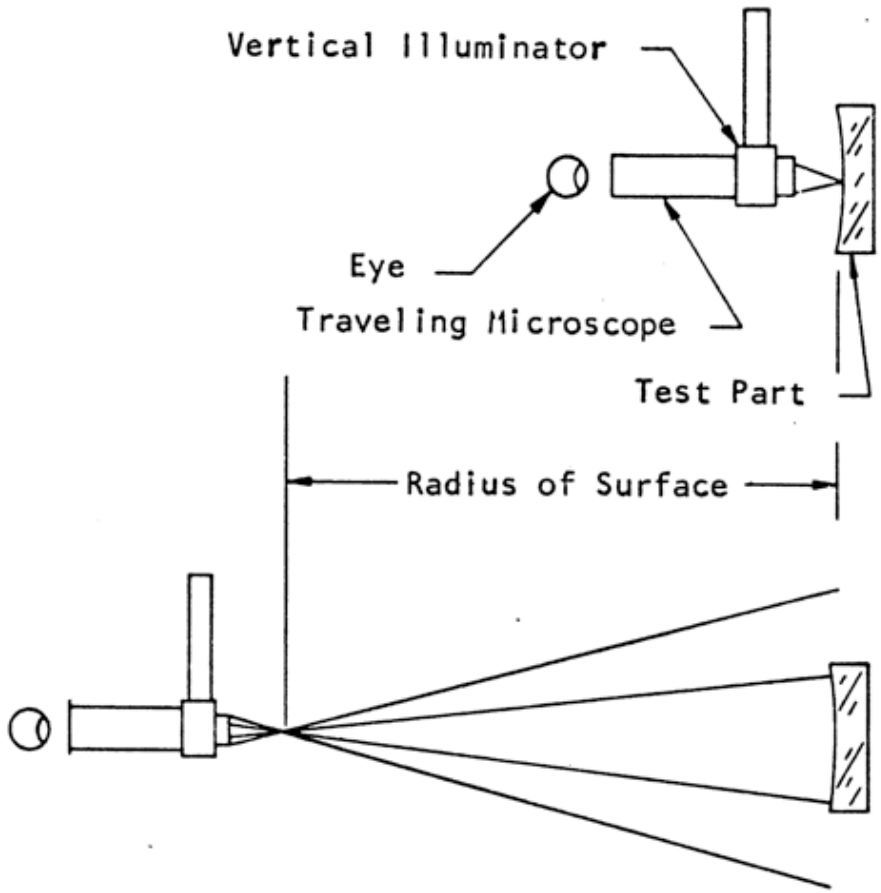
8.1.2 Autostigmatic Measurement

- A travelling microscope with a vertical illuminator is often used to measure the curvature of a surface directly.
- The instrument consists of a normal microscope configuration with a small beamsplitter placed behind the objective. A light source is placed off to the side of the beamsplitter by a distance equal to the separation of the eyepiece reticle from the beamsplitter.
- If the microscope is focused on a surface, an image of the source will be projected on the surface, and reimaged in the plane of the reticle by the microscope objective.

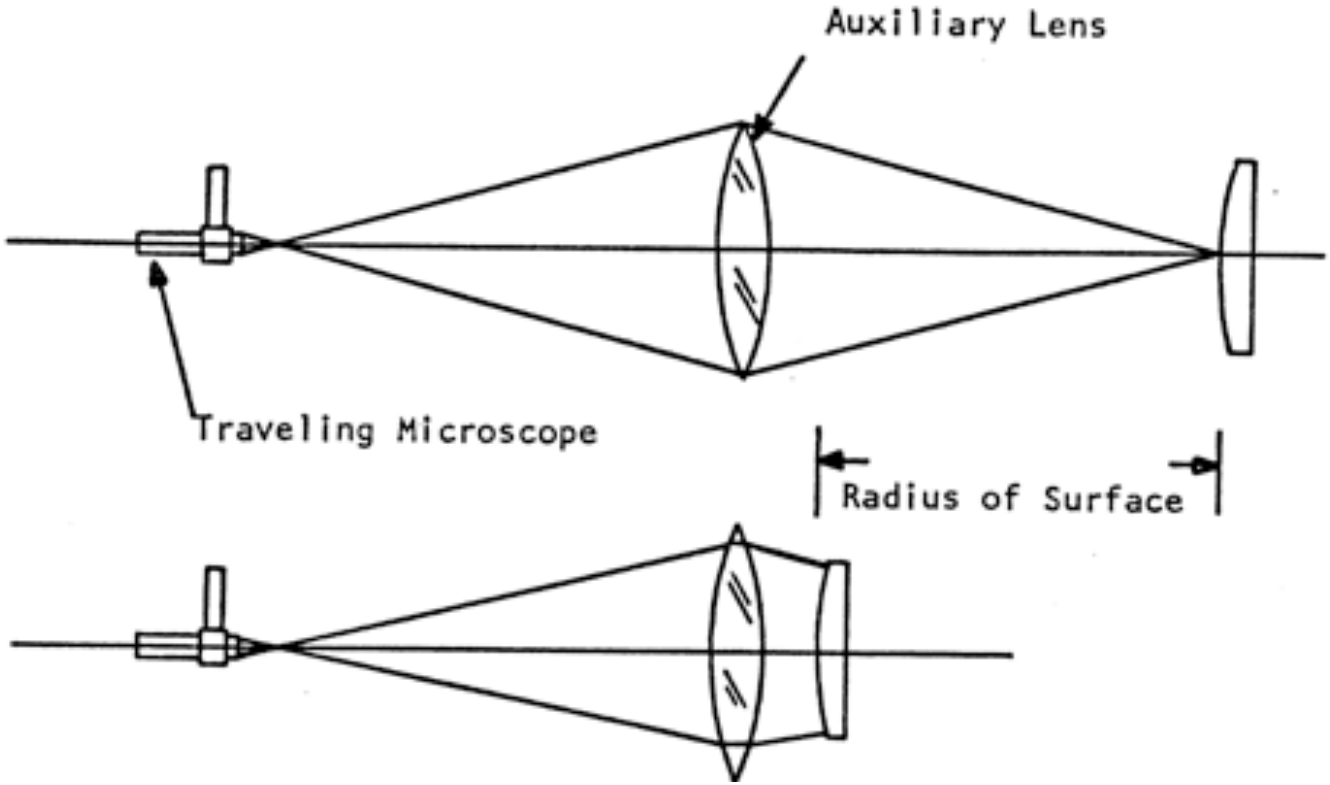
Autostigmatic Test for Measuring Surface Curvature

To measure the radius of curvature of a surface, the microscope is first focused on the surface, and then on the center of curvature of the surface. The separation of the two focus positions is equal to the radius of curvature of the surface.

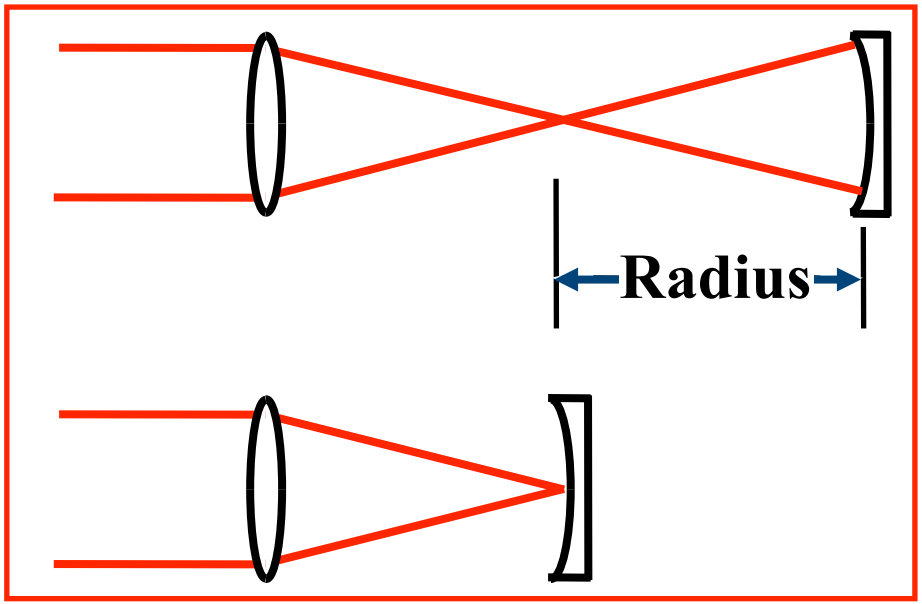


Measuring Convex Surfaces

A convex surface can be measured using an auxiliary positive lens.



Perform Measurement using Interferometer and Radius Slide



Two positions which give null fringe for spherical mirror.

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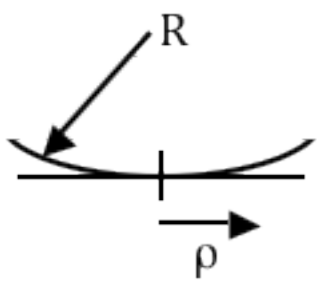
8.1.3 Newton's Rings

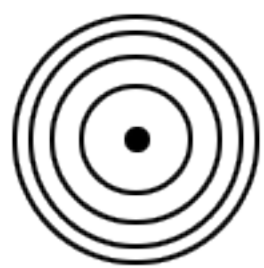
- A Fizeau interferometer can also be used to measure radius of curvature of a surface. A surface having a long radius of curvature can be compared interferometrically with a flat surface to yield Newton's rings.
- When viewed from above we see a series of concentric rings around a central dark spot. If R is the radius of curvature of the surface being measured, the radius ρ_m of the mth dark ring from the center is given by

$$\rho_m = \sqrt{m\lambda R}$$

$$R = \frac{\rho^2}{m\lambda}$$

m = order #





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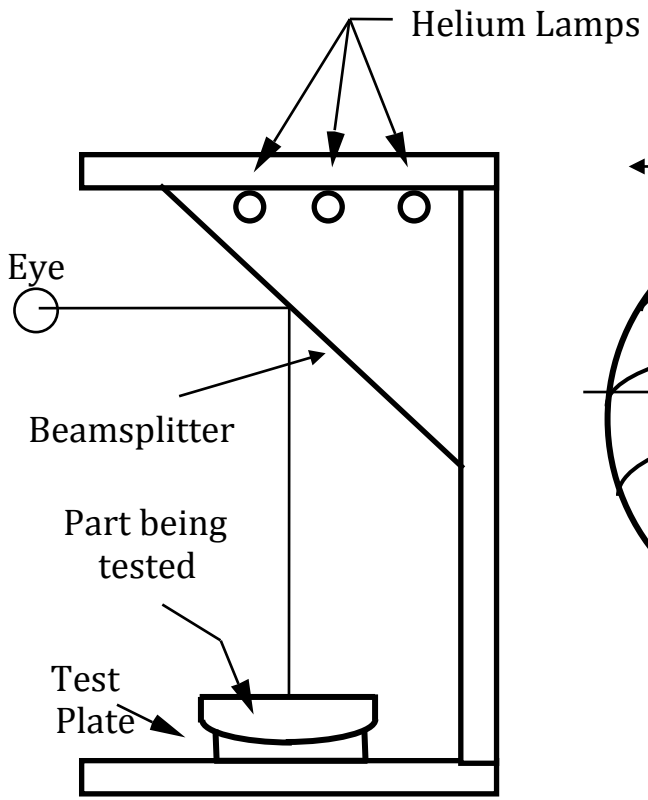
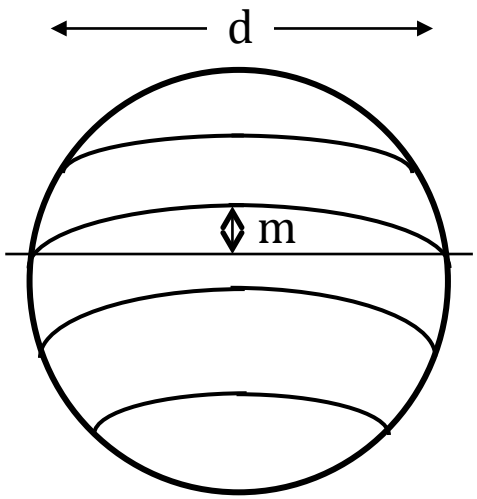
Measuring Shorter Radius of Curvature

Use reference surface of approximately the same radius of curvature as the surface being measured





$$\Delta R = \frac{4m\lambda R^2}{d^2}$$

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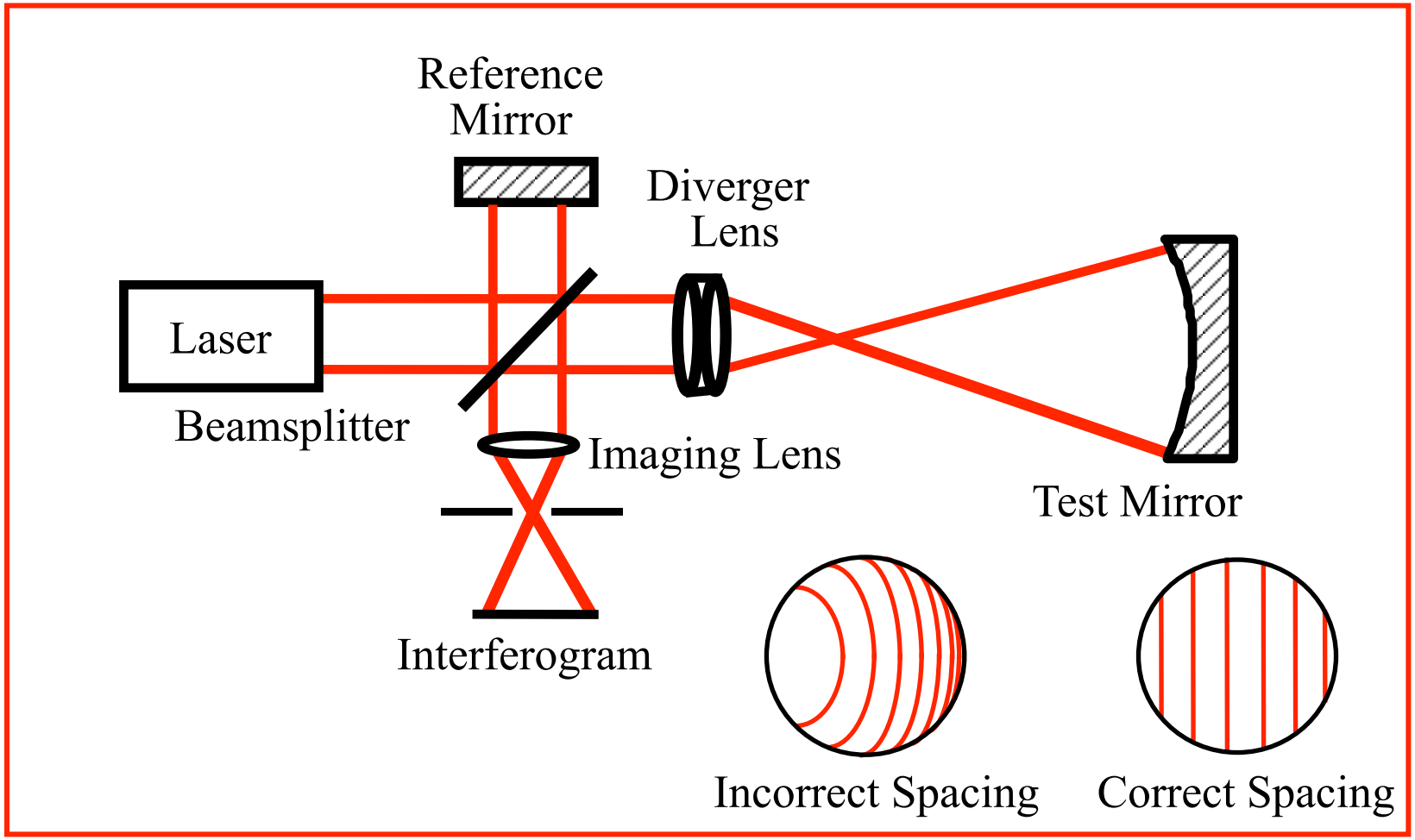
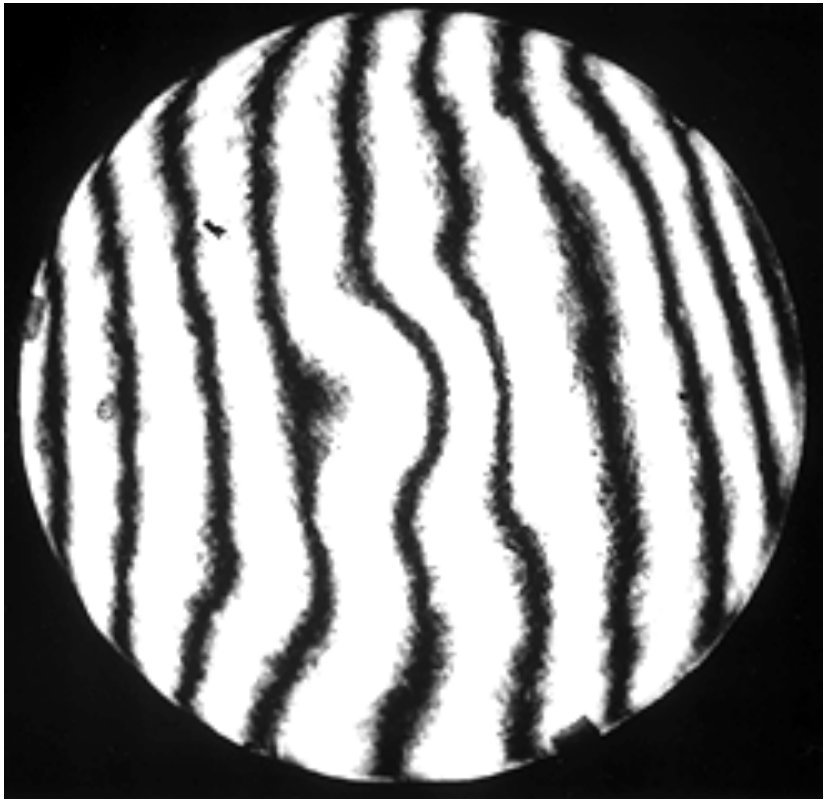
8.2 Measuring Surface Figure of Curved Surfaces

- **8.2.1 Test Plate**
  - We previously described the Fizeau interferometer for measuring surface flatness. The exact same procedure can be used to measure the surface figure of a curved surface, even an aspheric surface, if a reference surface is available. The interferograms as analyzed in the same manner as described above.
  - It should be noted that the two surfaces must have nearly the same radius of curvature if the resulting interferogram is to have a sufficiently small number of fringes to be analyzed.

8.2.2 Twyman-Green Interferometer (LUPI) (Spherical Surfaces)



Typical Interferogram



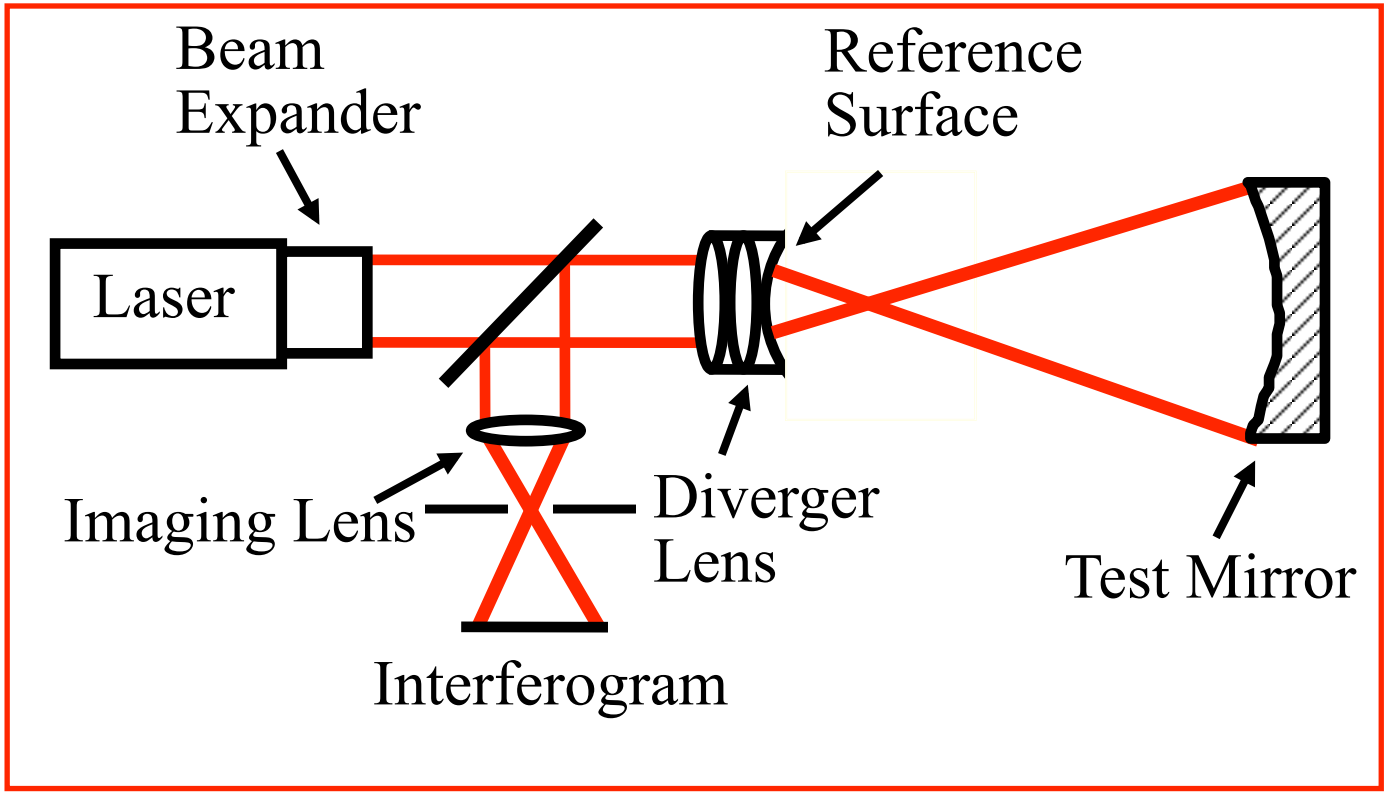
Comments on Twyman-Green (LUPI)

- A Twyman-Green interferometer with a laser source is sometimes called a LUPI (Laser Unequal Path Interferometer)
- The good features of the LUPI are
  - Any size concave optics can be tested
  - The two paths in the interferometer do not have to be matched as long as the conditions for coherence are satisfied
  - Surface contours are obtained just as for a test plate
  - The test is a noncontact test.
- The disadvantages are
  - The test is sensitive to vibration and turbulence
  - Expensive

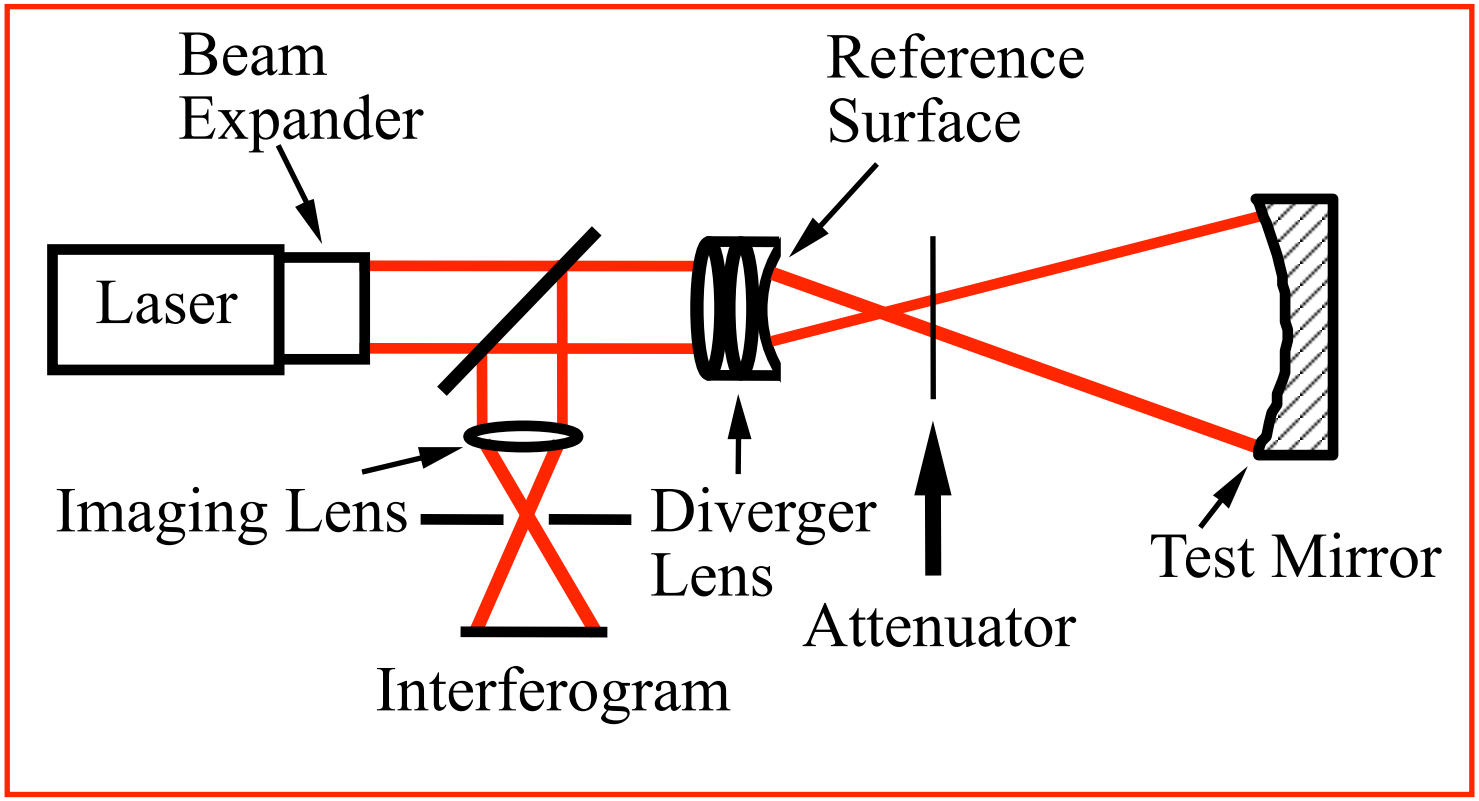
Reducing Bad Effects of Vibration

- Mounting the reference mirror on the surface being tested can reduce bad effects of vibrations. In this case the vibrations are coupled and the interference pattern will become much more stable.
- If the mirror is close to the interferometer a pencil or meter stick can be placed on top of the mirror and the interferometer to couple vibrations.

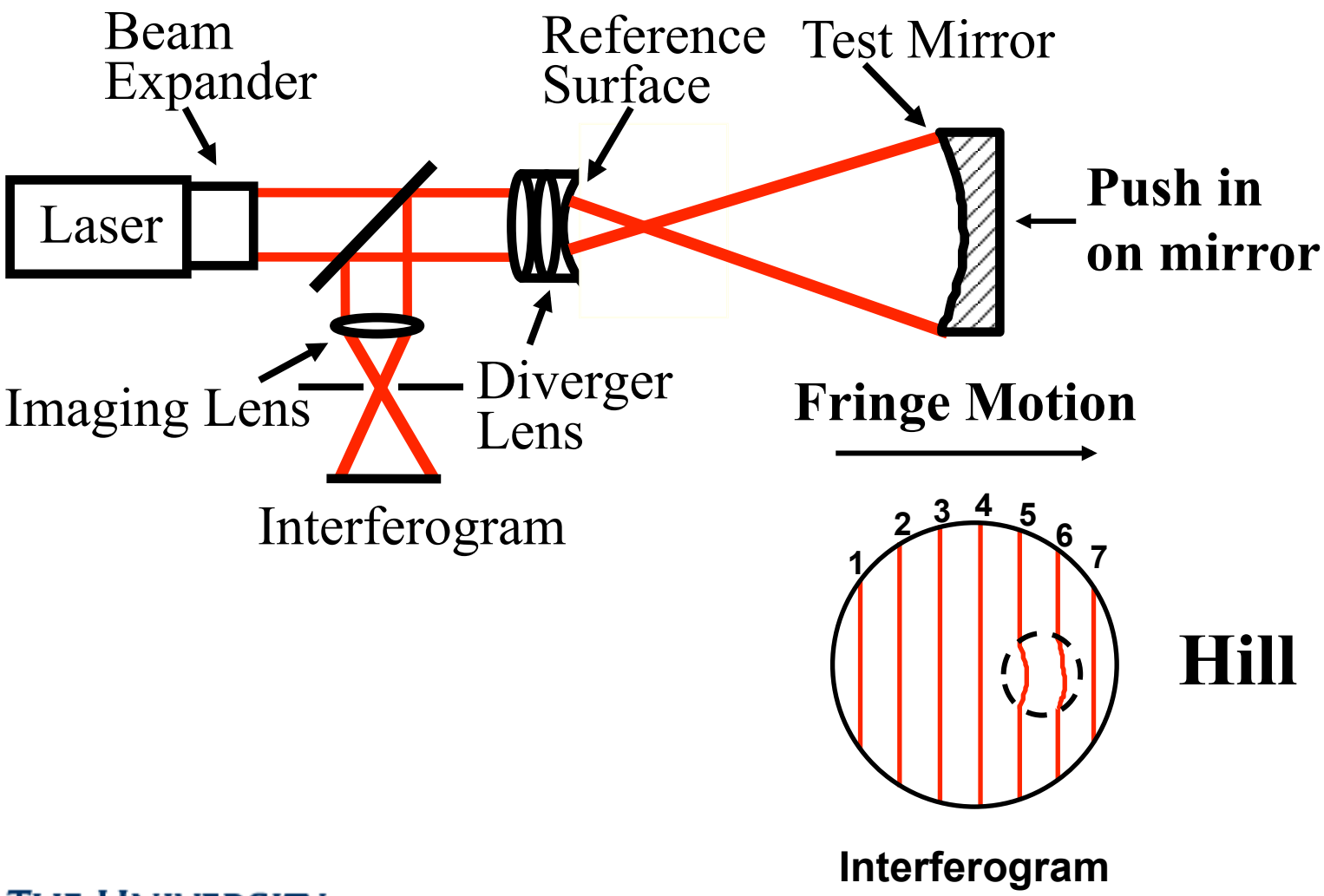
8.2.3 Fizeau Interferometer-Laser Source (Spherical Surfaces)



Testing High Reflectivity Surfaces



Hill or Valley?



Comments on Laser Based Fizeau

- The advantages of the laser based Fizeau compared to the Twyman-Green are
  - Quality requirements on diverger lens are less because of common path feature so cost is less
- The disadvantages are
  - Not as flexible
  - Not as light efficient
  - Common path makes it more difficult to do certain types of phase-shifting, such as the use of polarization techniques

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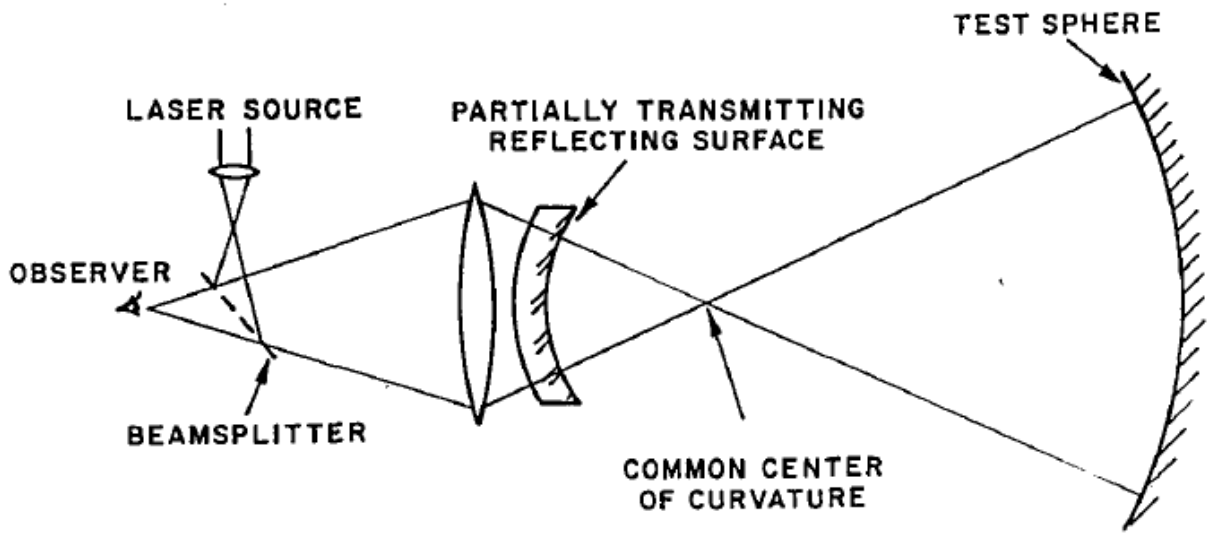
8.2.4 Spherical Wave Multiple Beam Interferometer (SWIM)

- Two high reflectance surfaces being compared in a Fizeau interferometer can yield sharp, high-finesse multiple-beam interference fringes.
- Must be careful about walk-off between the multiple beams.

SWIM for Testing Concave Surfaces



- Both the reference surface and the surface being tested must be coated.
- A lens placed at the common center of curvature of the two surfaces images one surface onto the other.
- A single longitudinal mode laser is required.

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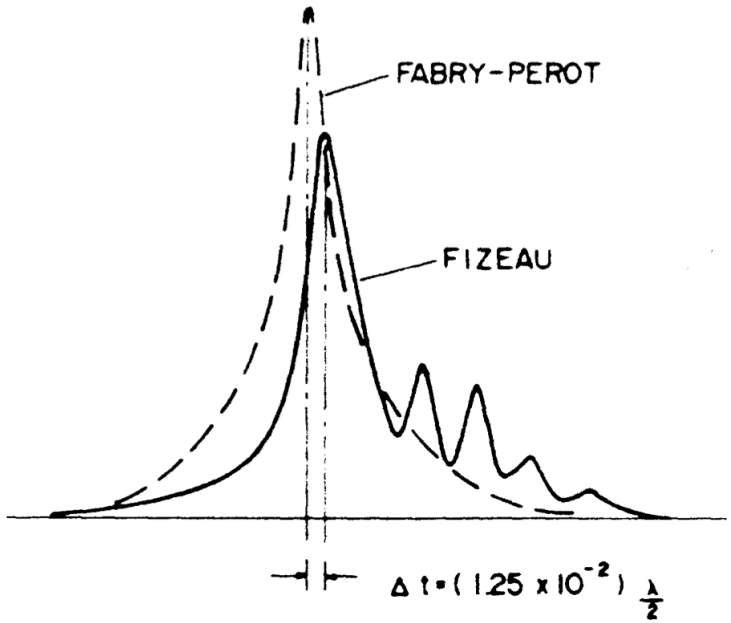
Walkoff Problem

The lens placed at the common center of curvature of the two surfaces is very important since, without it, any surface deformation in the mirror being tested or any displacement of the two centers of curvature will cause beam walkoff, which greatly reduces the fringe finesse.



Ref: K. Kinosita, "Numerical evaluation of the intensity curve of a multiple-beam Fizeau fringe," J. Phys. Soc. Jpn. 8, 219-225 (1953).

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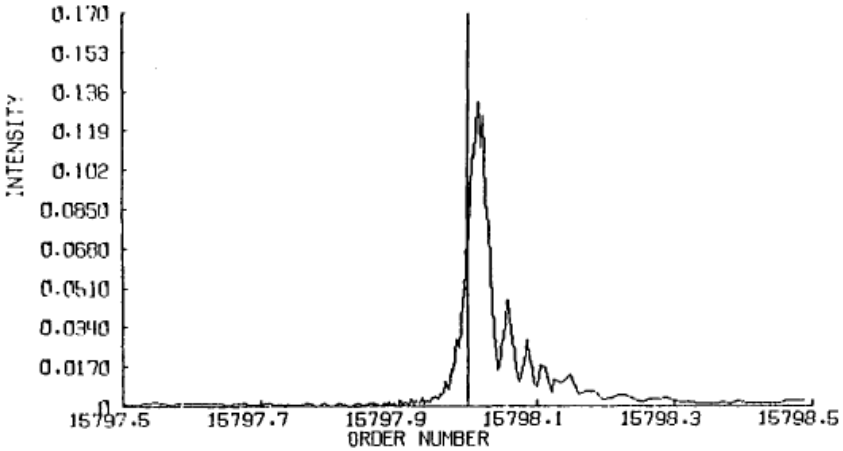
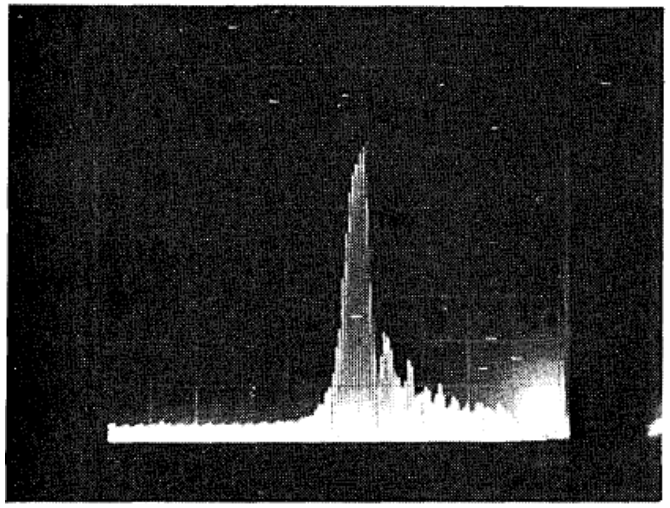
Fringe Shifts in Multiple-Beam Fizeau Interferometry





Computed and observed fringe profiles R = 98.4%, Fringe spacing = 6.4 mm, air gap = 4mm, λ = 514.5nm

Ref: J. R. Rogers, "Fringe shifts in multiple-beam Fizeau interferometry", J. Opt. Soc. Am., 72, 638-643 (1982)

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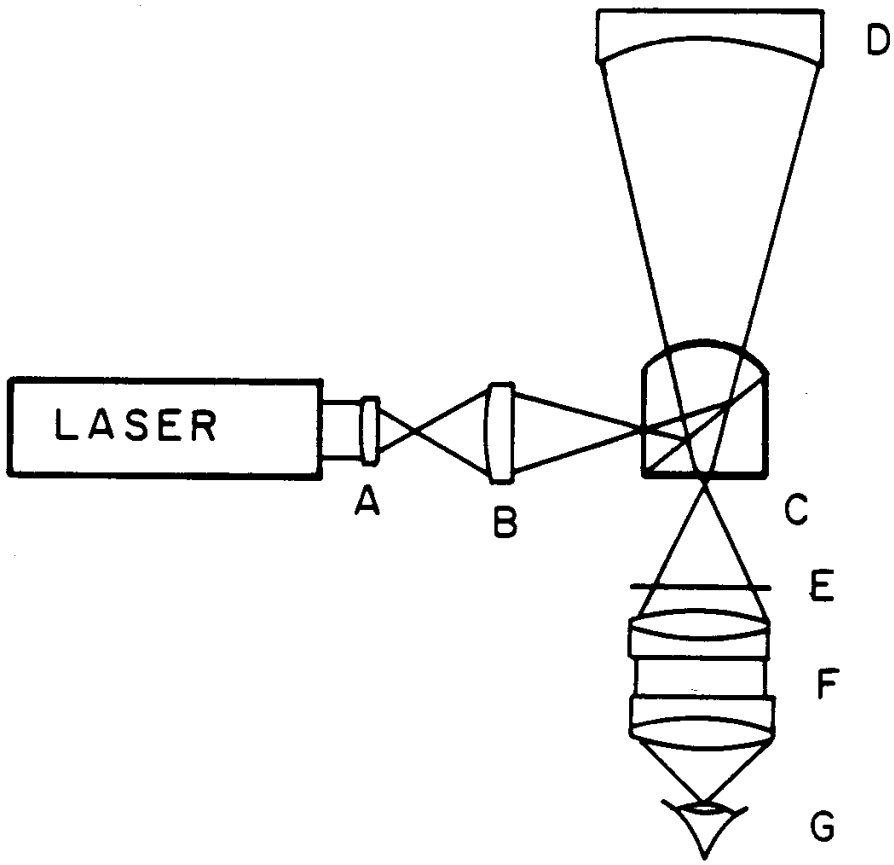
8.2.5 Shack Cube Interferometer



Ref: R. V. Shack and G. W. Hopkins, Opt. Eng. 18, p. 226, March-April 1979

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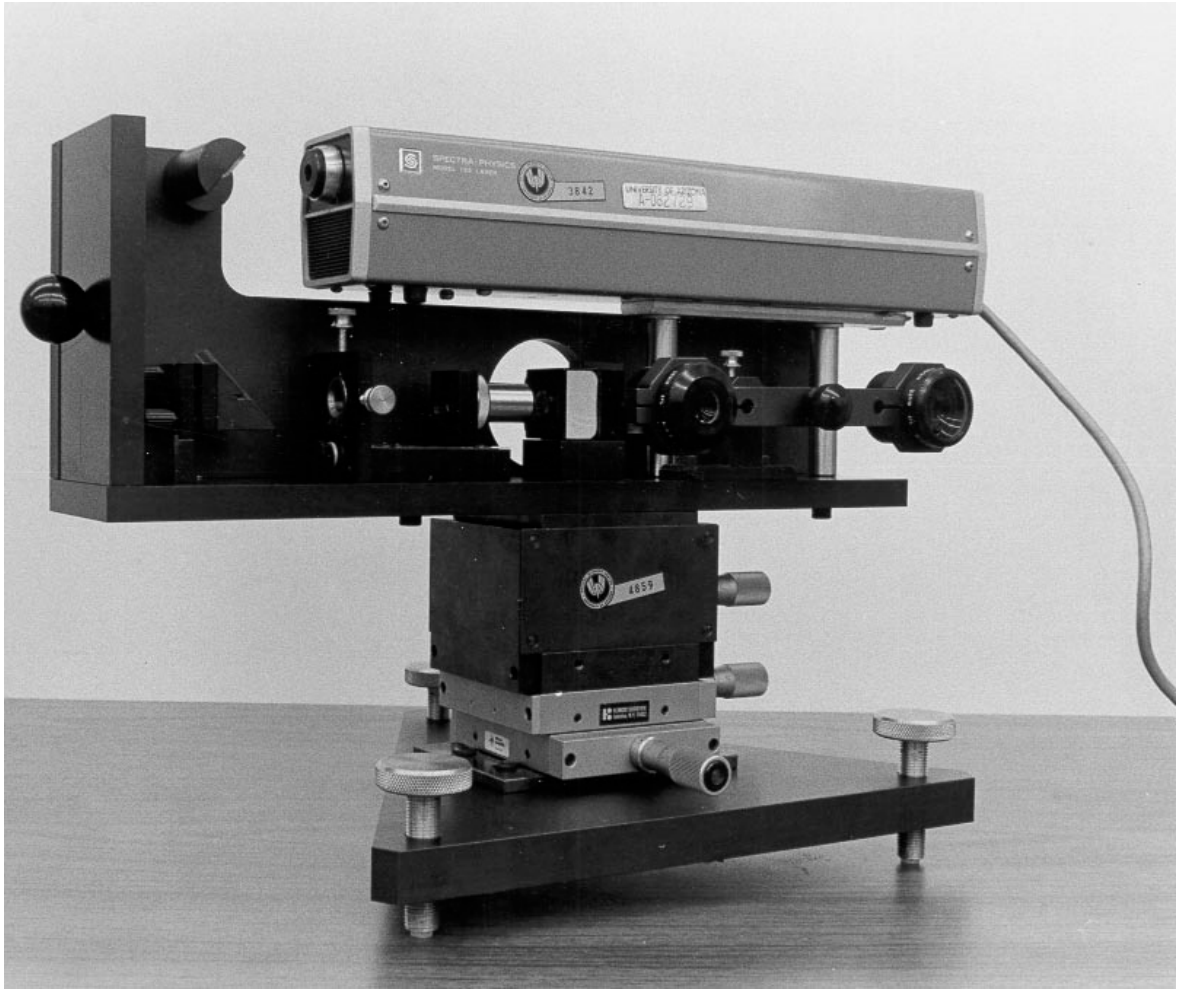
Shack Cube Interferometer



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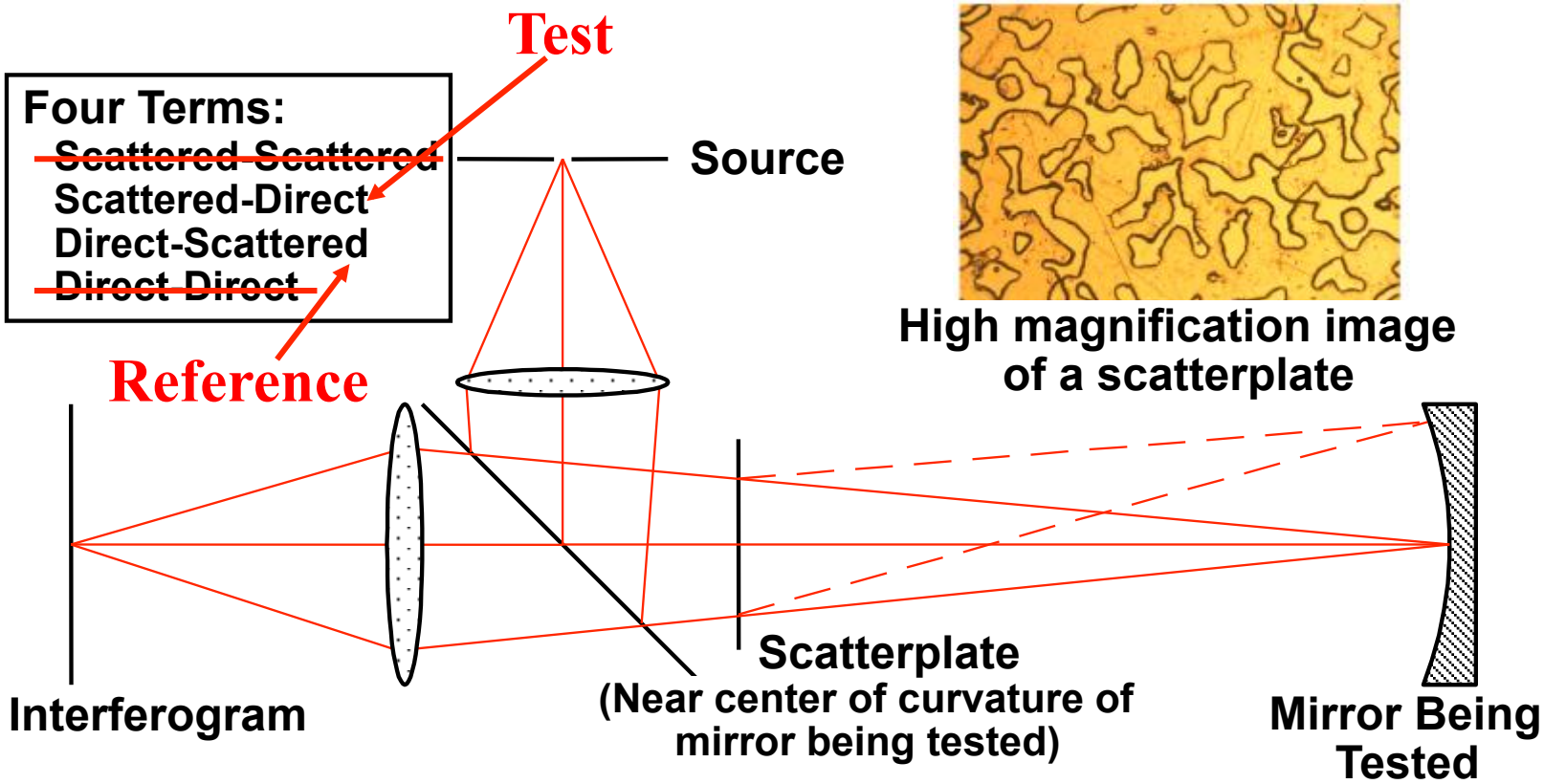
Comments on Shack Cube Interferometer

- Only 1 good surface required.
- Single longitudinal mode laser required.
- Accessory optics required for testing lenses or convex surfaces.
- Thin absorber, such as a pellicle, is required for testing coated surfaces.
- Lower cost, but not as flexible as Twyman Green or regular laser based Fizeau interferometer.

8.2.6 Scatterplate Interferometer

- Requires no high quality optics
- Common path
  - Less sensitive to vibration
  - Less sensitive to air turbulence
  - Source can be almost anything including a white light source
- Scatterplate
  - The critical component is the scatterplate
  - Must have inversion symmetry
  - Can easily(?) be made

Scatterplate Interferometer



High magnification image of a scatterplate

- Scatterplate has inversion symmetry
- Scatterplate is located at center of curvature of test mirror
- Direct-scattered and scattered-direct beams produce fringes

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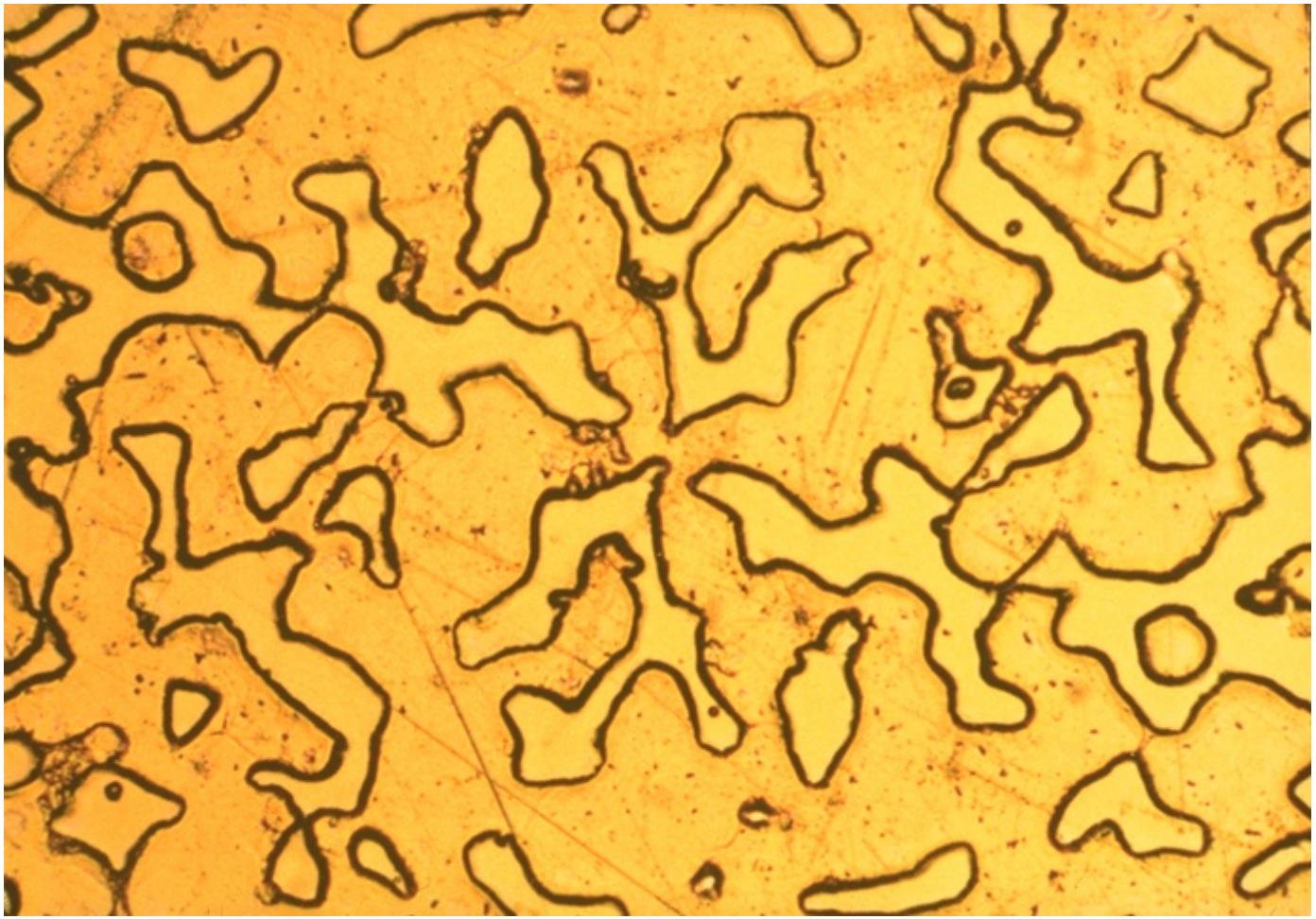
Microscopic Image of Scatterplate



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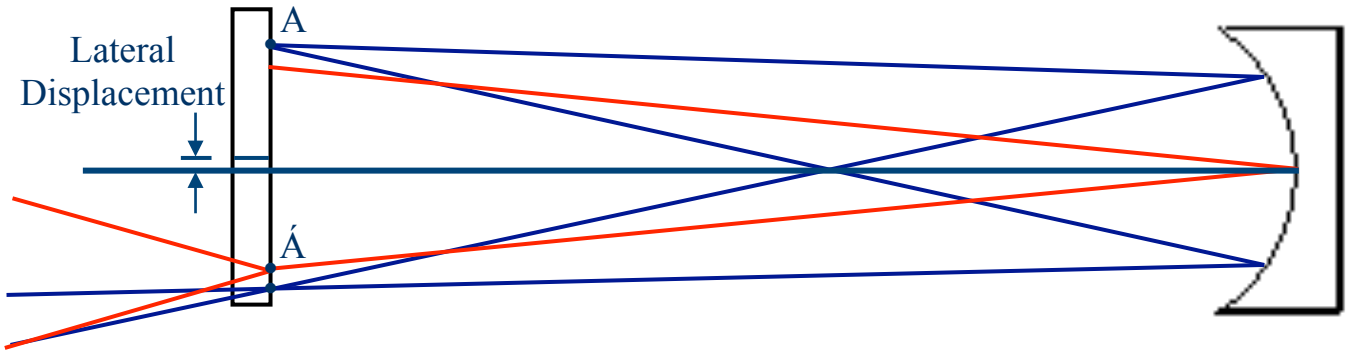
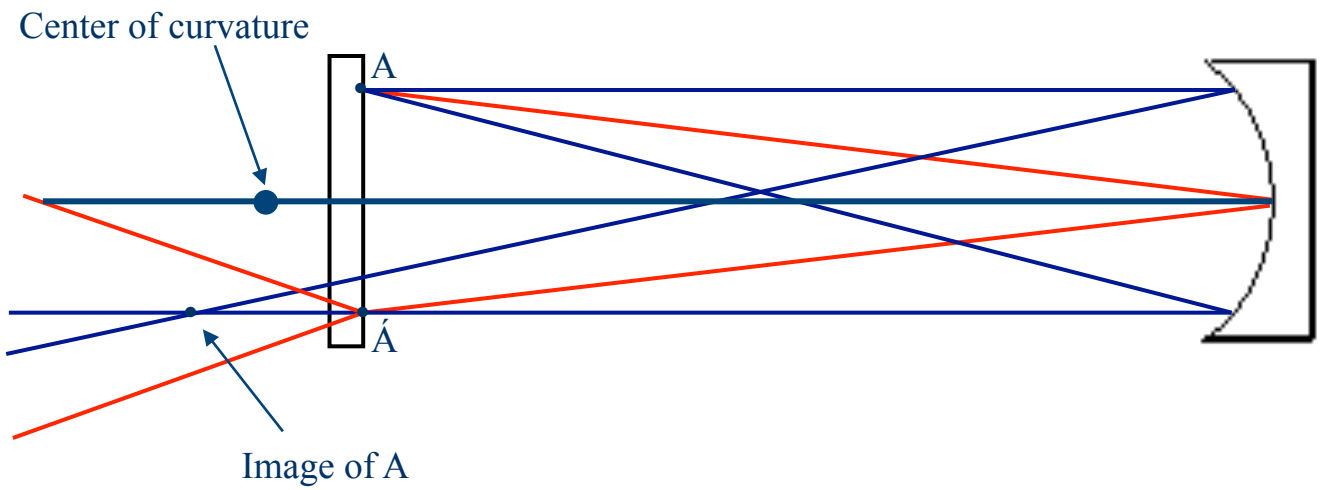
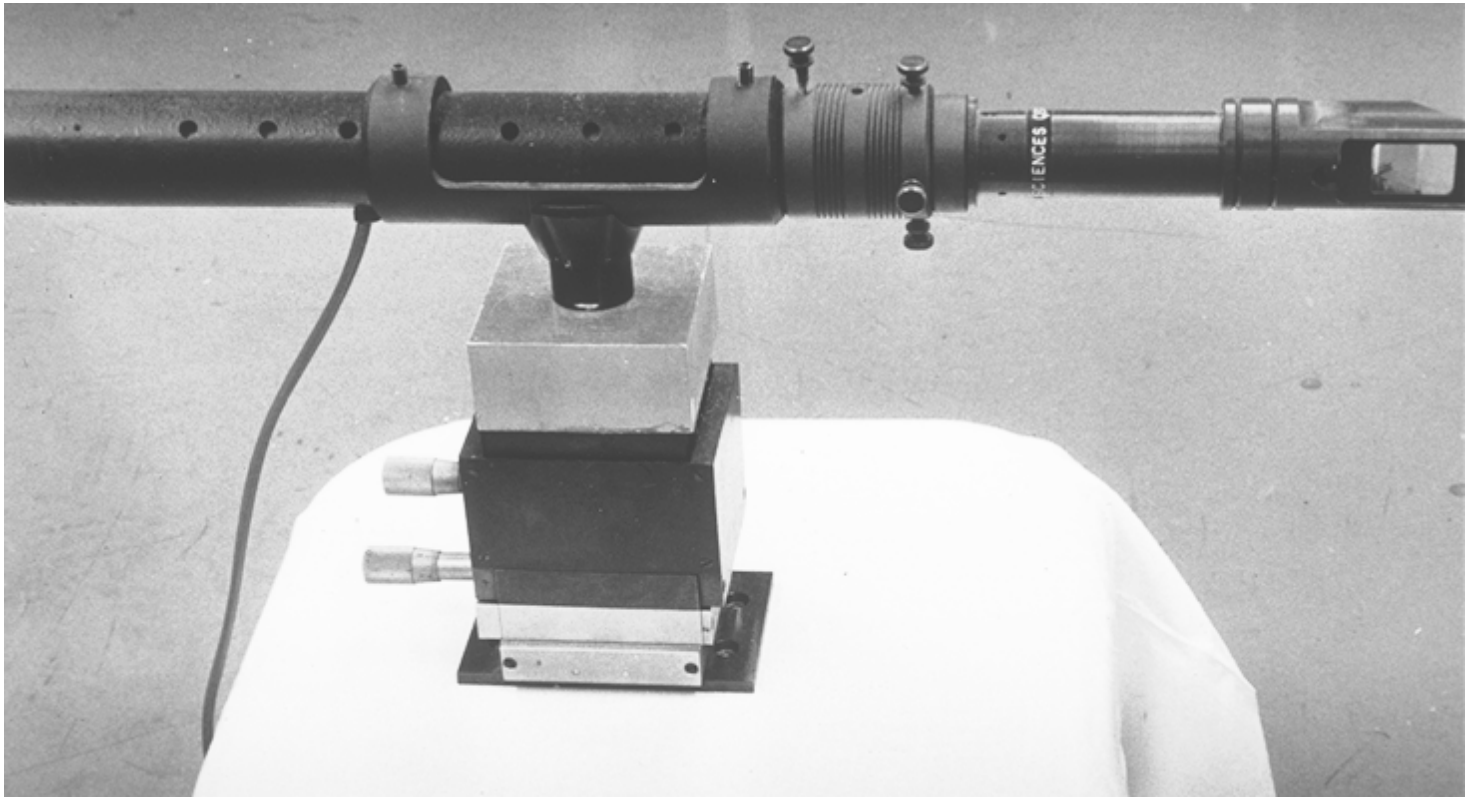
Lateral Displacement Introduces Tilt



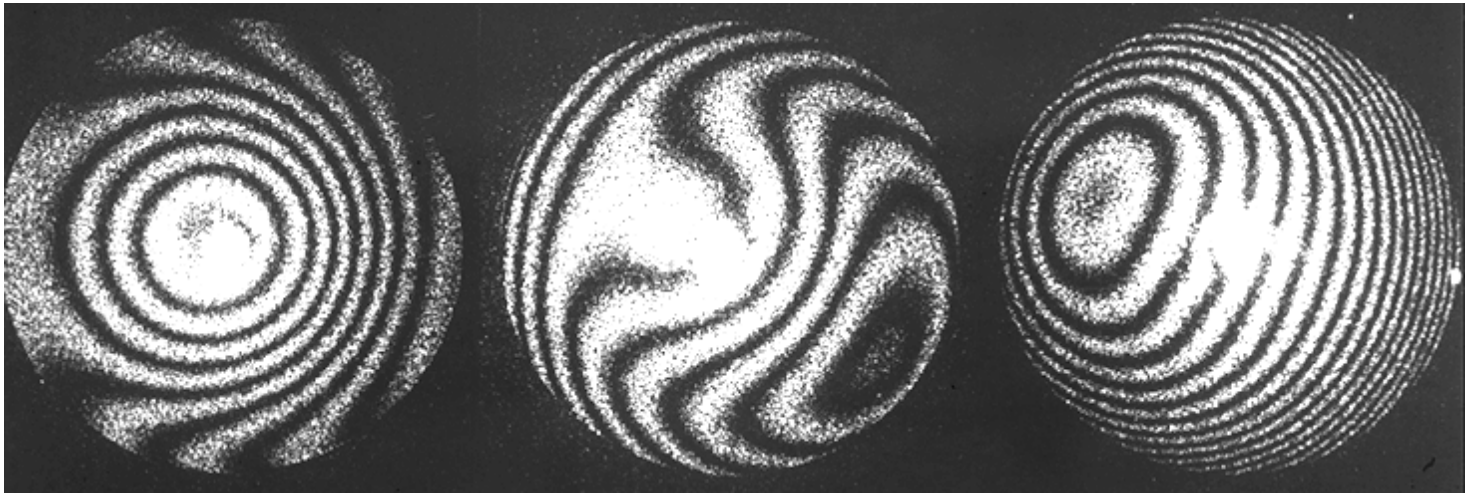
Longitudinal Displacement Introduces Defocus



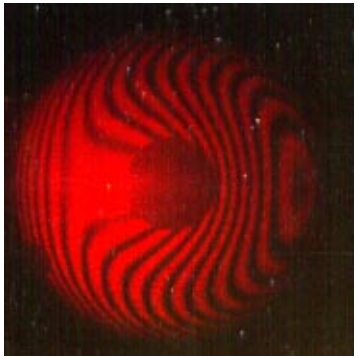
Scatterplate Interferometer



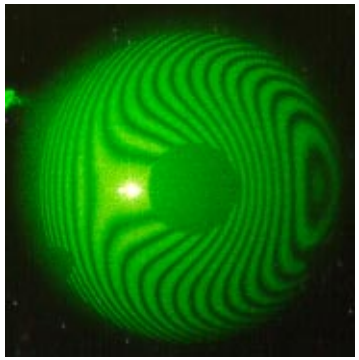
Scatterplate Interferograms



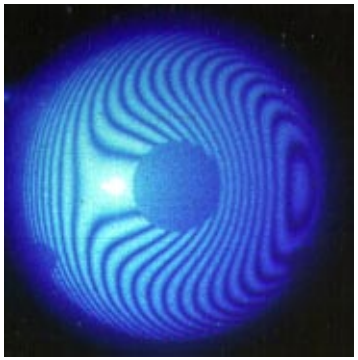
Scatterplate Interferograms



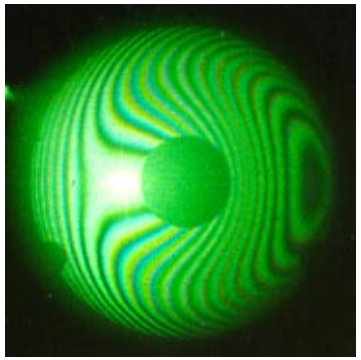
647.1 nm



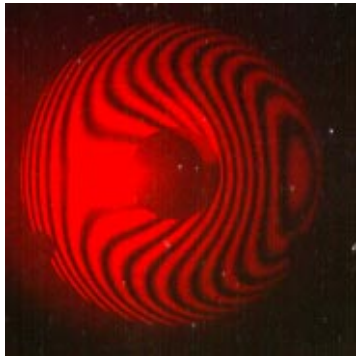
520.8 nm



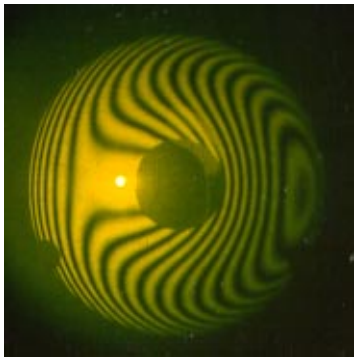
476.2 nm



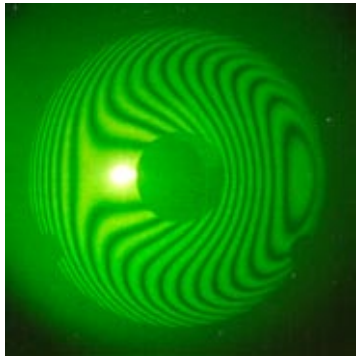
All λ's except red



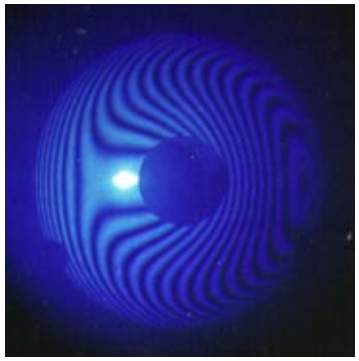
Absorptive scatterplate



568.2 nm, rotating ground glass



520.8 nm, rotating ground glass



476.2 nm, rotating ground glass

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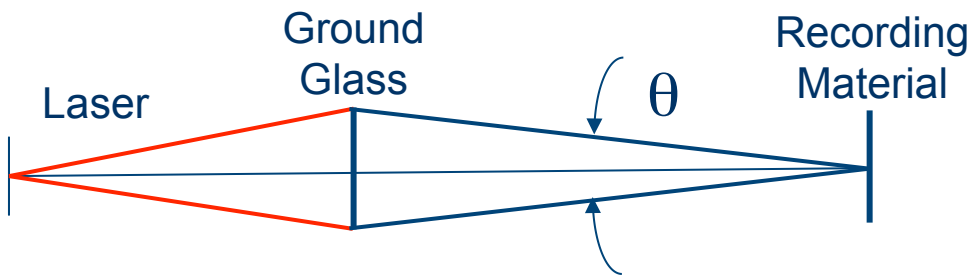
Comments

- OPD is zero for fringe passing through hot spot. That is, the fringe passing through the hot spot is always the “zero order” fringe.
- Image of source on interferogram must be smaller than the fringe spacing. One-half fringe spacing is about the largest practical size.
- If laser used as source there are speckles in interferogram. Speckles can be eliminated if the laser beam is focused on a rotating ground glass.
- If scatterplate is too large, off-axis aberrations will reduce fringe contrast and can cause error. If two small, resolution bad and speckles can become too large. 0.5 to 1 cm diameter is typical size.

Making a Scatterplate – Two Techniques

- **Recording a speckle pattern**
  - Illuminate a piece of ground glass with a laser beam and record speckle pattern on film or photoresist.
  - After first exposure rotate recording medium 180° to within 1 arc sec and make a second recording. This gives us the inversion symmetry we want.



θ determines speckle size and scattering angle of scatterplate

- **Generate on computer**
  - Use electron beam recorder to record computer generated scatterplate pattern

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J. M. Burch, Nature, Vol. 171 (4359, 889-90 (May 16, 1953)

Scatter Fringes of Equal Thickness

It is possible to test an optical system by means of white-light interference between two or more wave-fronts which have been scattered by equivalent obstacles out of the same collimated beam.

Consider, for example, an optical system in which a small portion of the field is strongly illuminated with white light. If a screen of moderate scattering power (say, a microscope slide which has been aluminized while in contact with a piece of lens tissue) is introduced into the entrance pupil, then the observer sees the remainder of the field stop illuminated by a diffuse diffracted halo. If a second exactly conjugate screen is placed in the exit pupil so that it appears identical with the image of the first screen except for imaging errors and for some relative displacement, white-light fringes are formed on the field stop by the two scattered beams.

Where the first screen is seen imaged without sensible error, for example, by a plane mirror, the fringes observed are of equal inclination, well-known examples being Newton's diffusion fringes and Quetelet's rings. If, on the other hand, the first screen is being imaged by an imperfect system and is adjusted to nominal coincidence with its fellow, corresponding fringes of equal optical thickness are produced. Light scattered by the first screen suffers distortion by the system to form the error wave-front; but the second or reference wave-front is substantially free from error since its parent beam has traversed that system in concentrated fashion. The fringe pattern therefore represents the wave-front error with which the entrance pupil is being imaged on to the exit pupil, a bright achromatic fringe covering those portions of the field for which the transit time is the same as for the directly illuminated patch.

The practical possibilities of these fringes of equal thickness do not seem to have been explored. For optical testing they have one advantage in that they do not lose contrast in the presence of considerable tilt or asphericity. Of particular interest is their application to imaging systems of unit magnification such that one screen is (1) imaged by a through type or autostigmatic system on to an identical replica; (2) imaged back on to itself enantiostigmatically; or (3) repeatedly imaged on to itself in a multiple-beam arrangement.

Preliminary experiments on the first two types suggest that the fringes may be useful for testing large mirrors, camera lenses and microscope objectives, and possibly for interference microscopy. The fact that the fringes are self-compensating for path-length and, in the second case, for odd azimuthal errors suggests various engineering applications. Further investigation is taking place.

J. M. Burch

H. H. Wills Physical Laboratory,
Royal Fort, Bristol 8.
Dec. 9.

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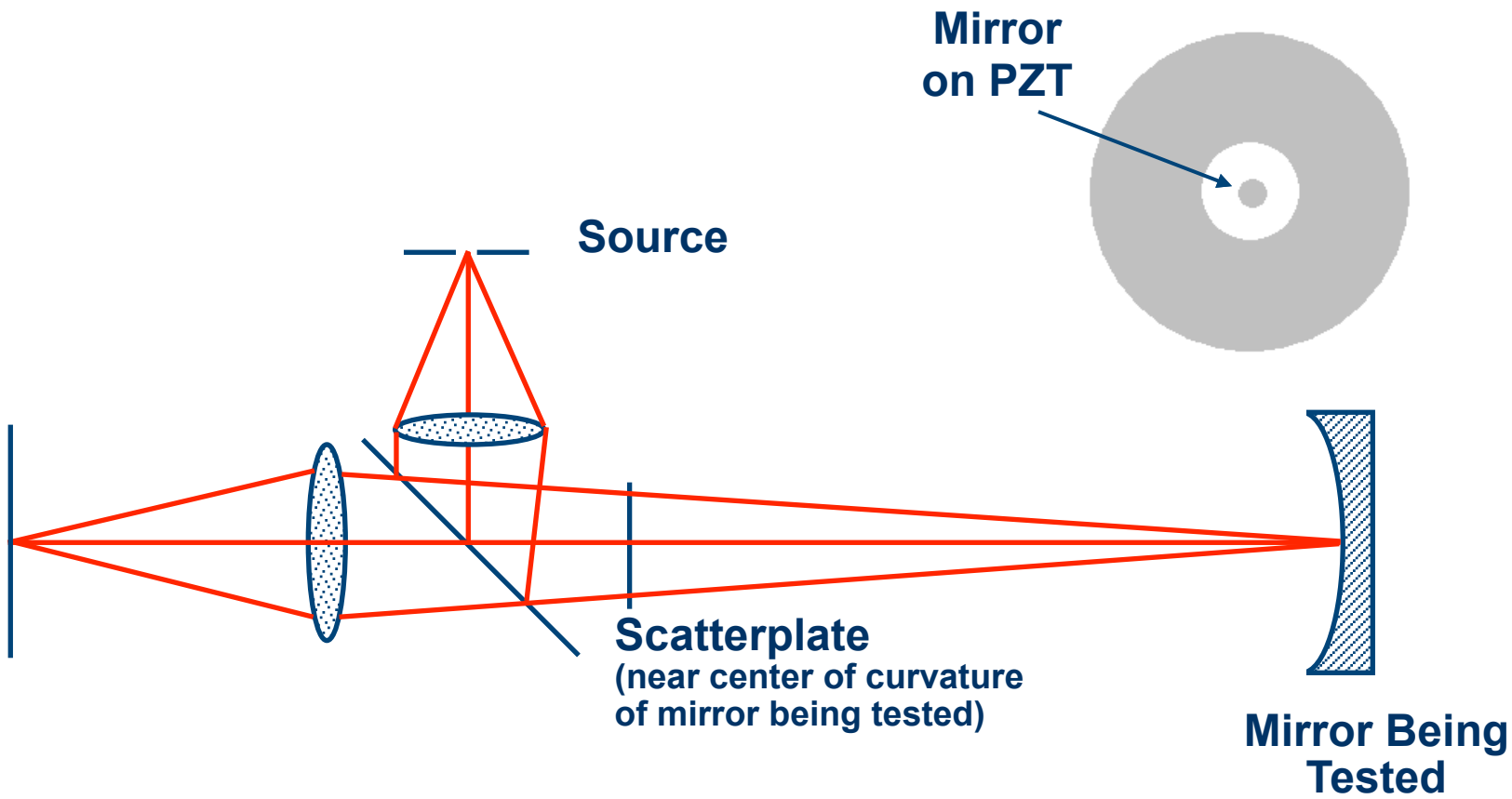
Phase-Shifting Scatterplate Interferometer

- Difficult to phase-shift because both test and reference beams traverse the same path
- Two approaches for phase-shifting
  - Focus unscattered beam on mirror mounted on PZT
  - If Test and Reference Have Orthogonal Polarization then Phase-Shifting is Possible

Phase-Shifting Scatterplate Interferometer



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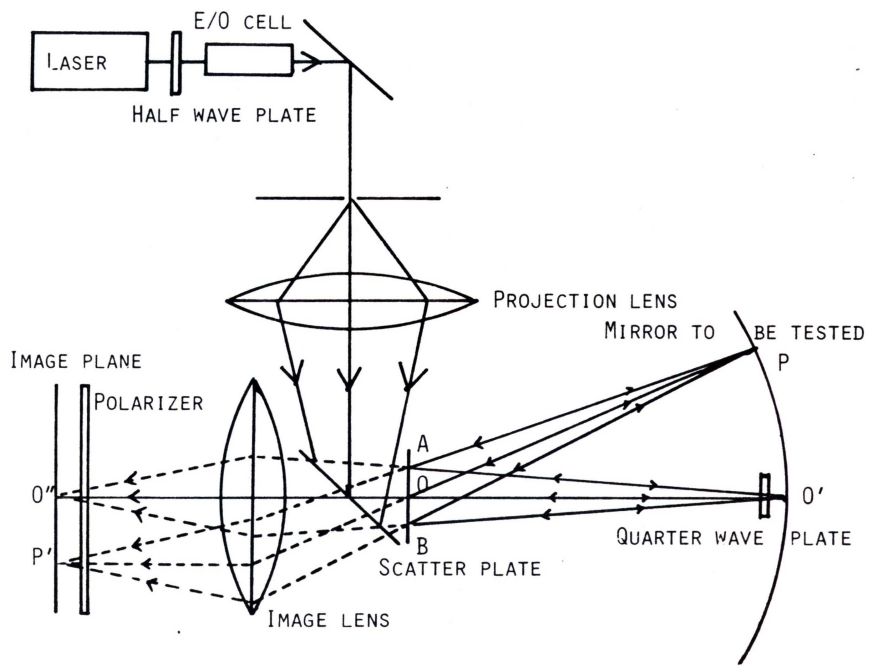
Phase-Shifting Scatterplate Interferometer

- Phase shift between x and y polarizations produced by applying voltage to E/O Cell.
- Direct beam passes through a 1/4 wave-plate twice and direction of polarization rotated 90°. X and y polarizations switched.
- Polarizer passes one direction of polarization (say x).
- Must correct for phase error produced by 1/4 wave-plate.



Ref: Huang, J., Honda, T., Ohyama, N., and Tsujiuchi, J., Opt. Commun., 68, 235, 1988.

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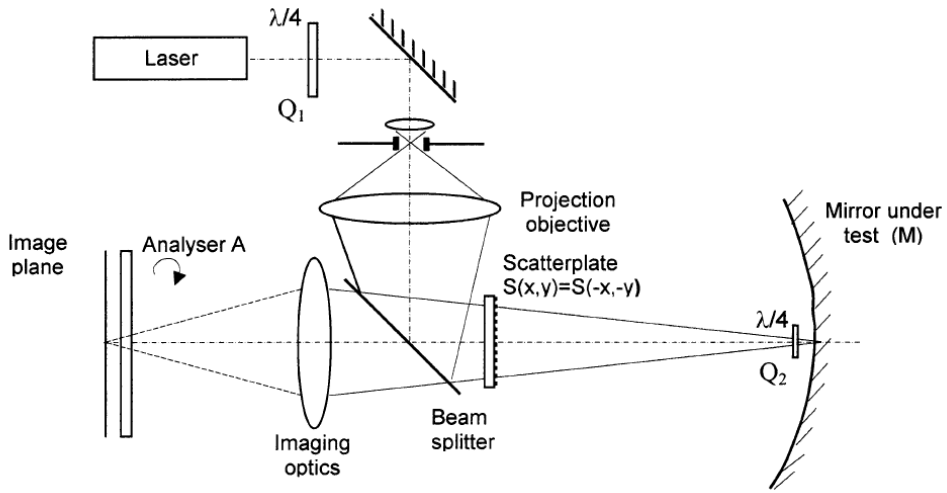
Phase-Shifting Scatterplate Interferometer

- Circularly polarized light incident.
- λ/4 plate used to change handedness of direct beam.
- Rotating analyzer changes phase shift between left-handed and right-handed test and reference beams.
- Must correct for phase error produced by 1/4 wave-plate.



Ref: K. Patorski and L. Salbut, Proc. of SPIE Vol. 5144, 234-239, 2003.

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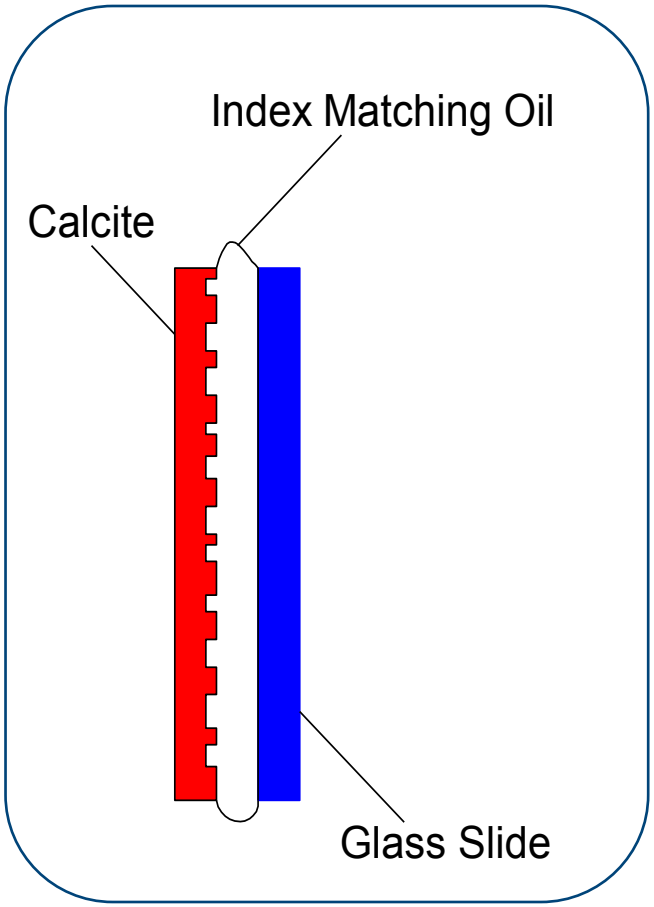
Birefringent Scatterplate Makes Phase Shifting Possible

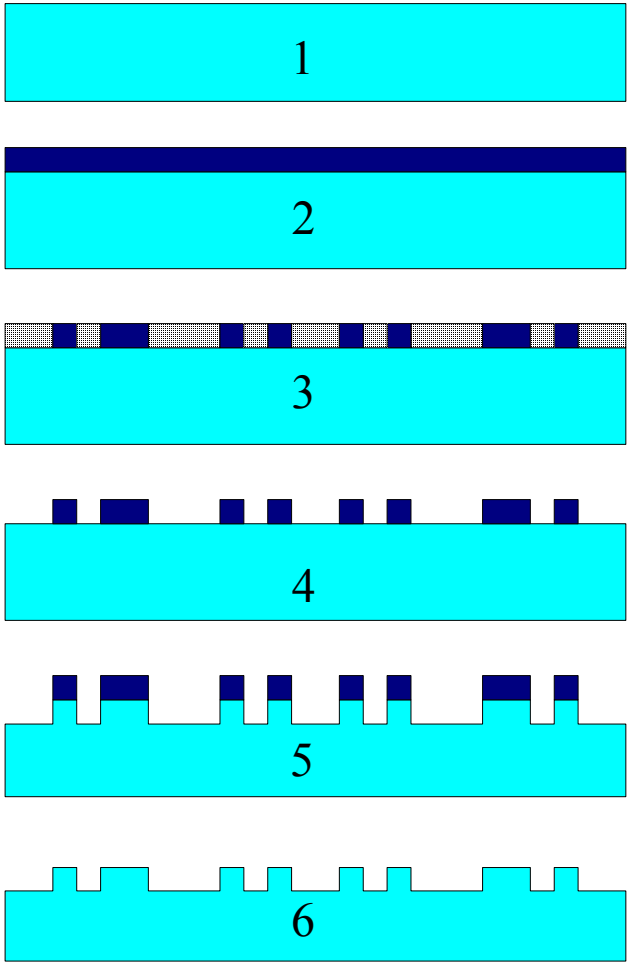
- Scatterplate is Made of Calcite
- Oil Matches Ordinary Index of Calcite
- Scattering is Polarization Dependent



Scatterplate Production

Generated using six step process

1. Clean substrate
2. Spin coat with Photoresist
3. Expose
   - Holographic
   - Photomask
4. Develop
5. Etch with 37% HCl
   Diluted 5000/1 in DI
6. Remove Photoresist



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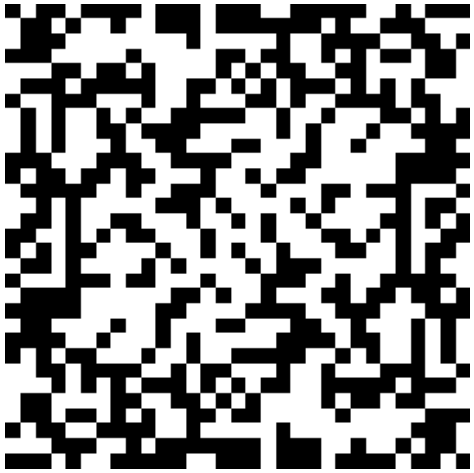
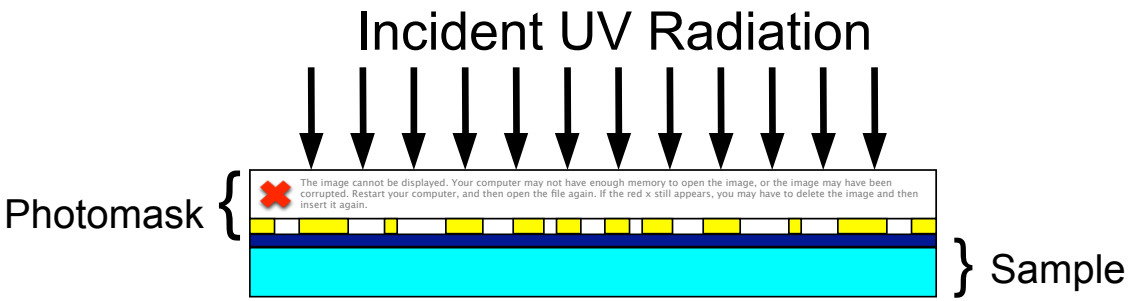
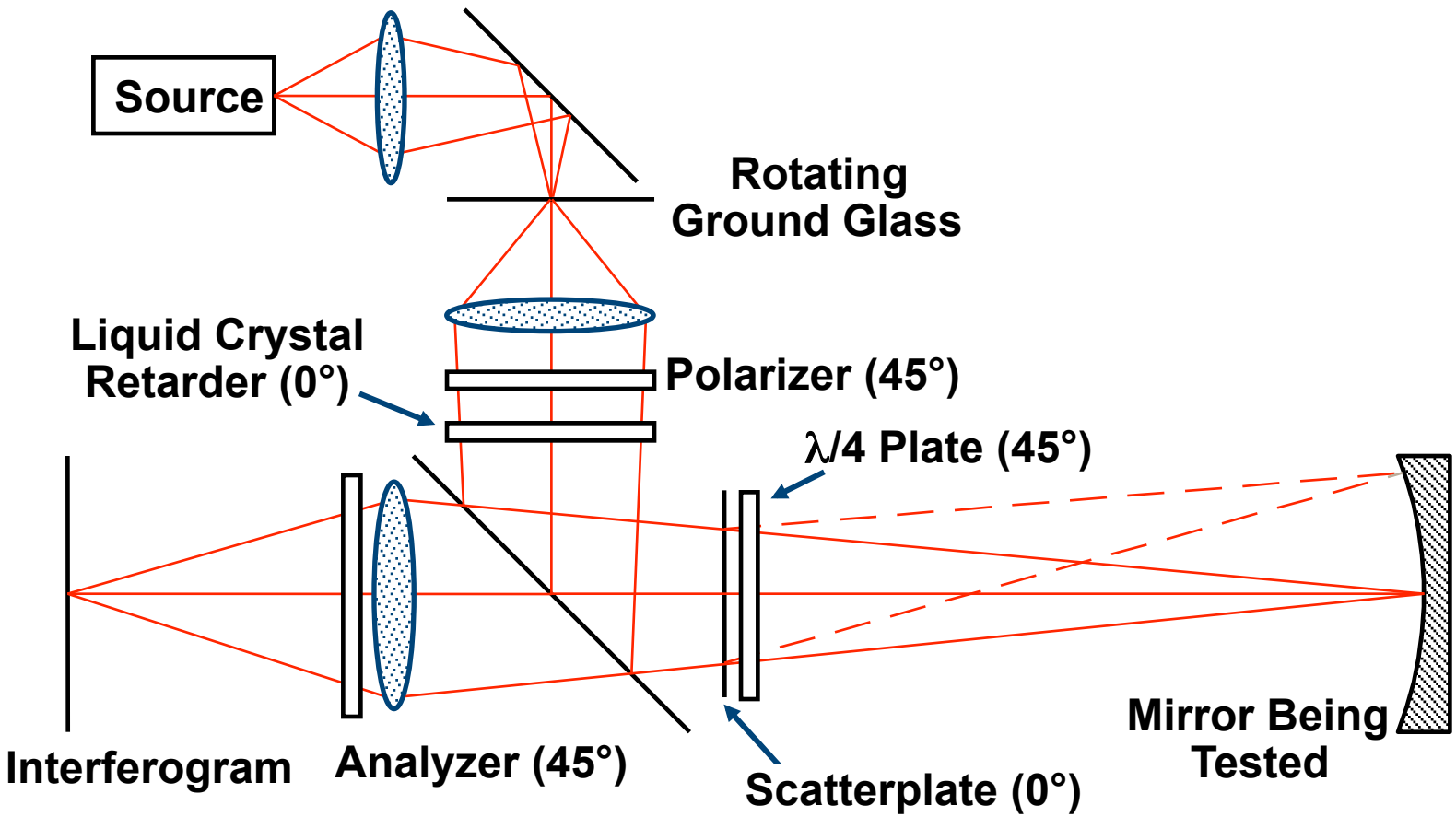
Photomask Exposure

- Desired pattern is designed in computer
- Pattern is written into chrome on a quartz substrate using an electron beam
- UV source illuminates photoresist only where chrome has been removed





Phase-Shifting Scatterplate Interferometer



Ref: Michael B. North-Morris, Jay VanDelden, and James C. Wyant, APPLIED OPTICS, Vol. 41, page 668, February 2002.

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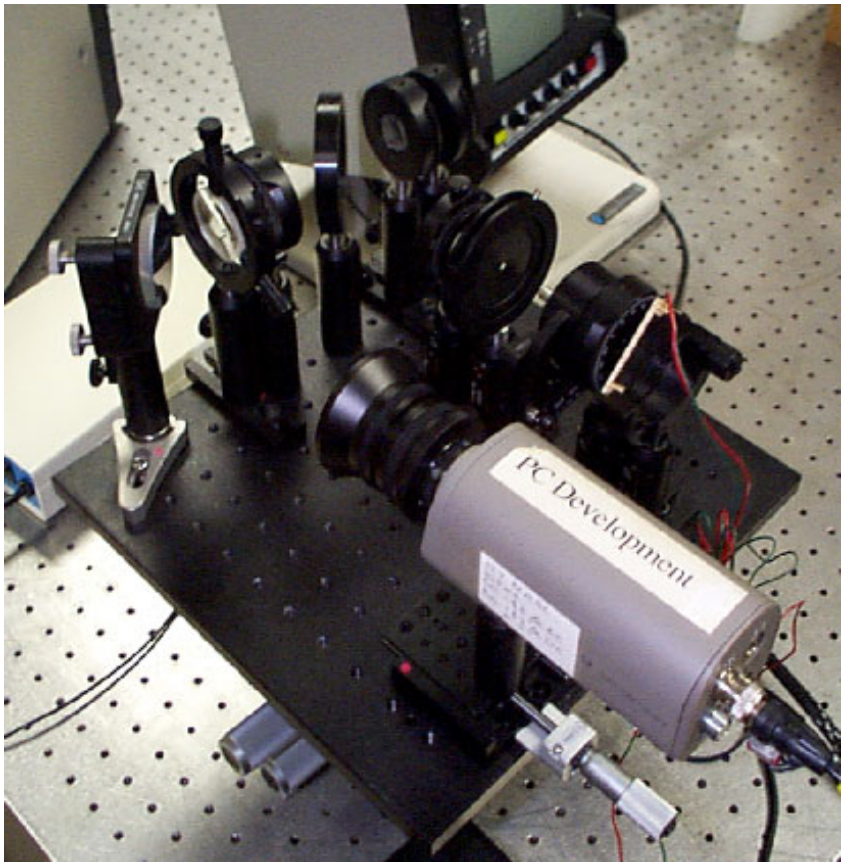
Phase-Shifting Scatterplate Interferometer



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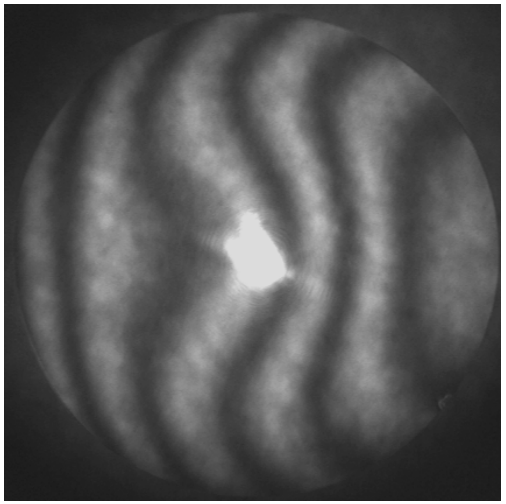
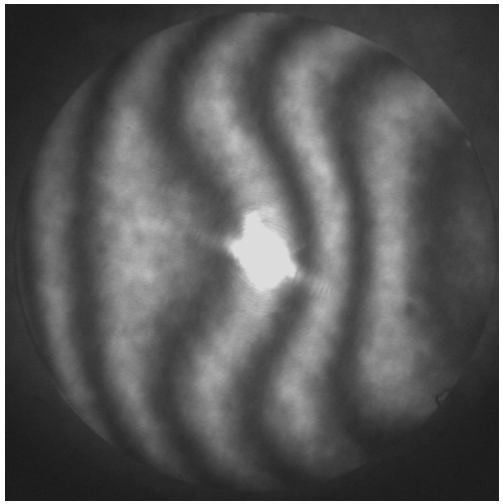
Phase-Shifted Fringe Pattern

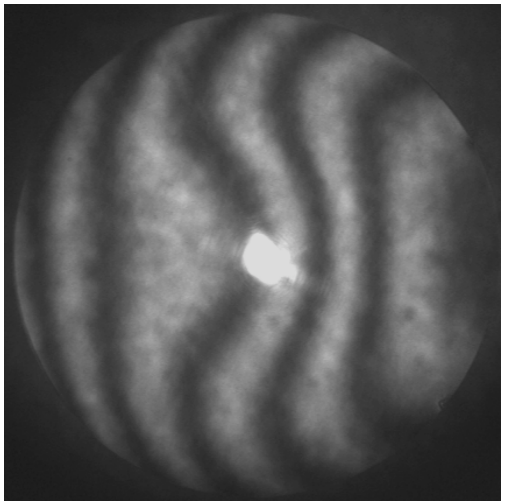
Frame 1

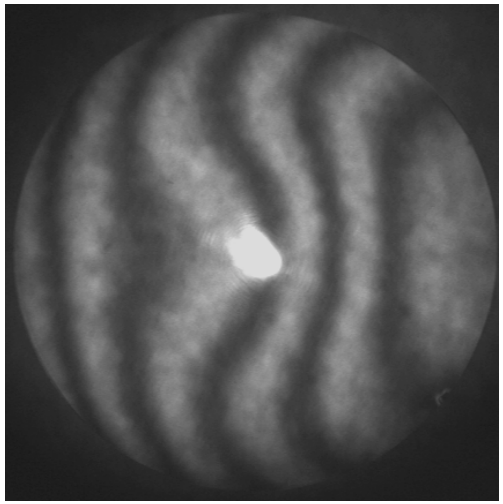




Frame 2

Frame 3





Frame 4

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Surface Measurement Using Phase-Shifting Scatterplate Interferometer

Surface Statistics:

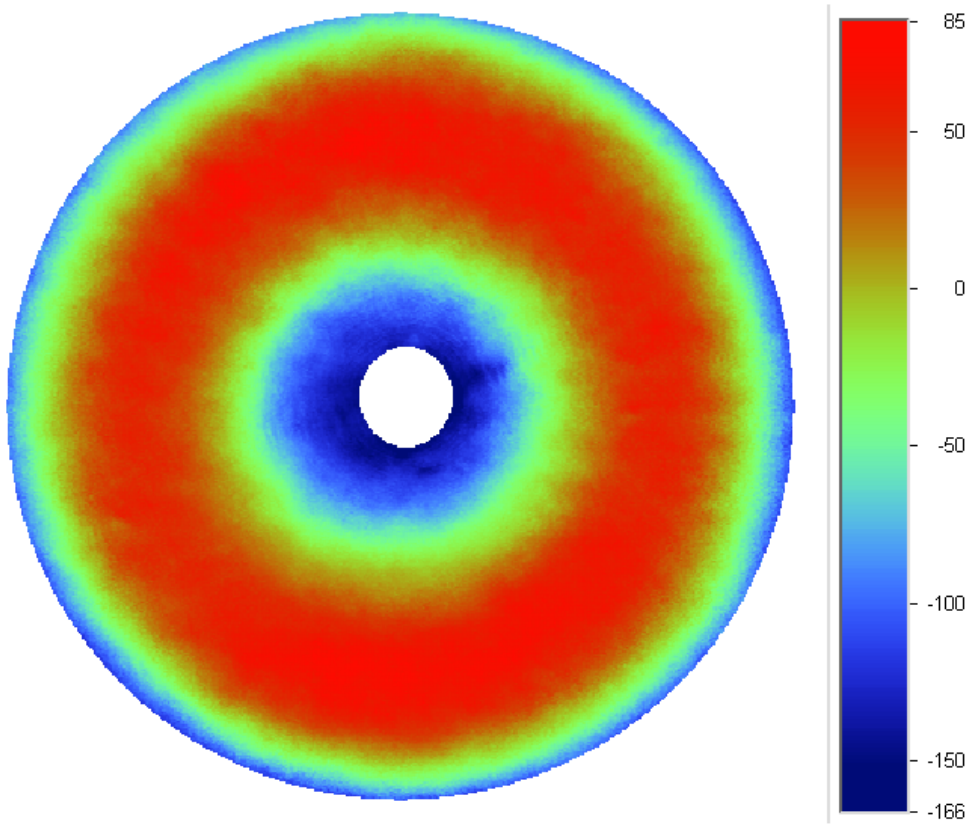
Ra: 46.78 nm
Rq: 55.31 nm
Rz: 237.37 nm
Rt: 251.29 nm

Set-up Parameters:

Size: 451 X 431
Sampling: 0.00 mm

Processed Options:

Terms Removed:
None
Filtering:
None



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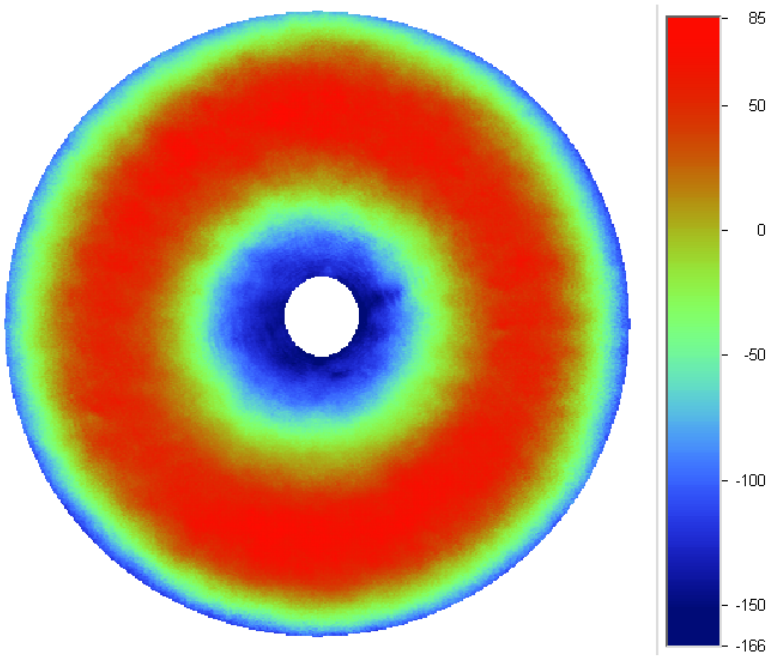
Measurement Comparison

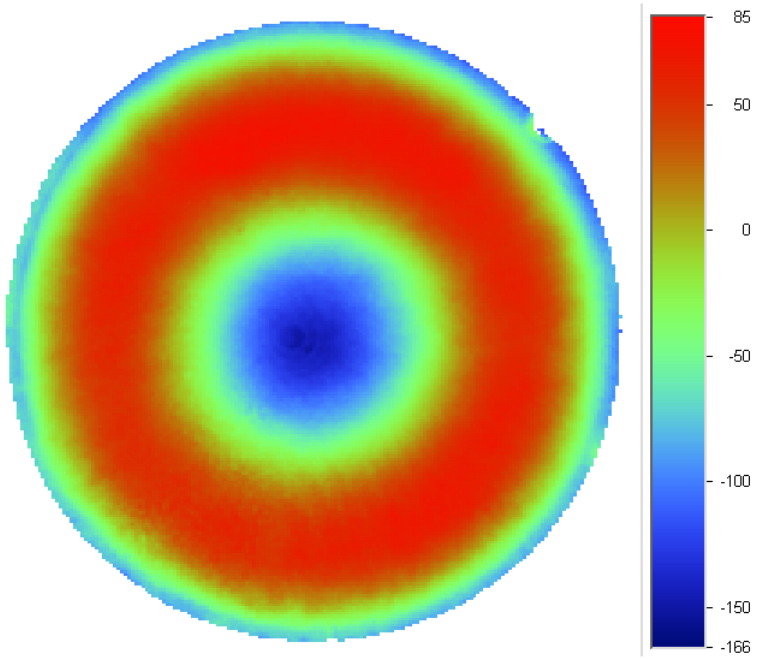
Scatterplate



RMS = 0.008738 Waves

PV = 0.03750 Waves

WYKO 6000



RMS = 0.008738 Waves

PV = 0.03405 Waves

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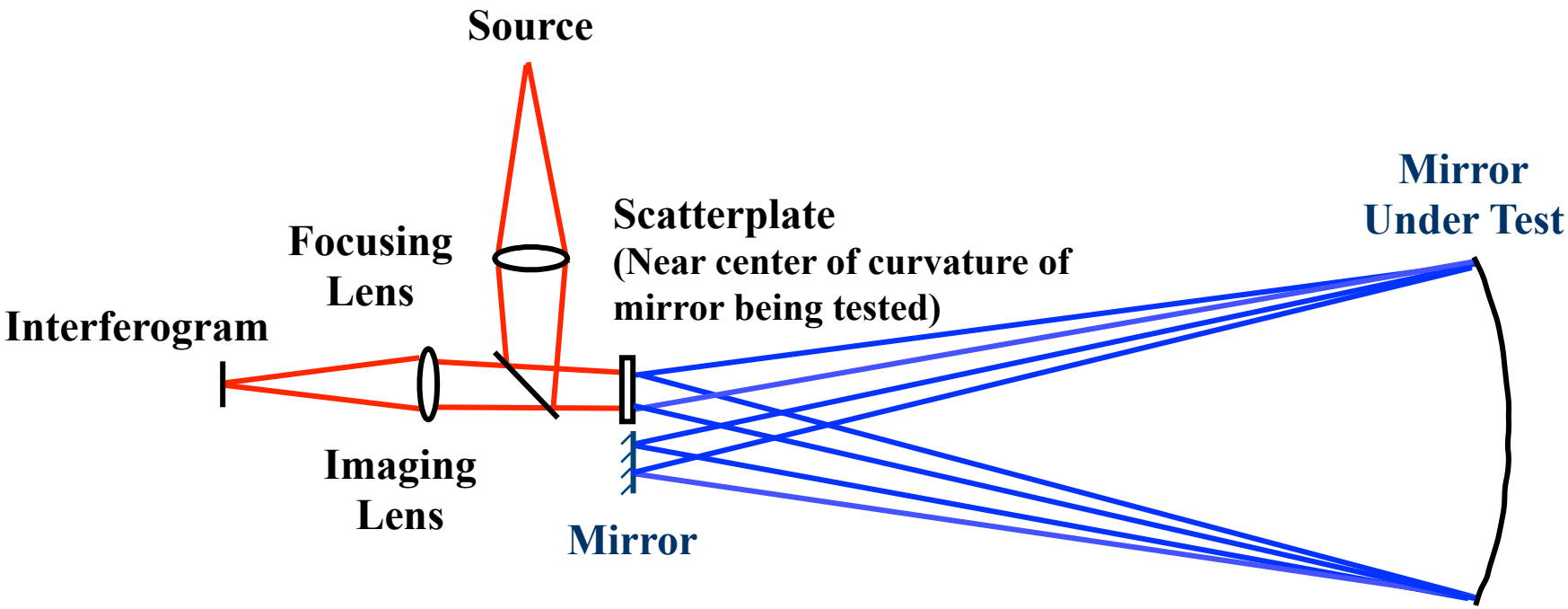
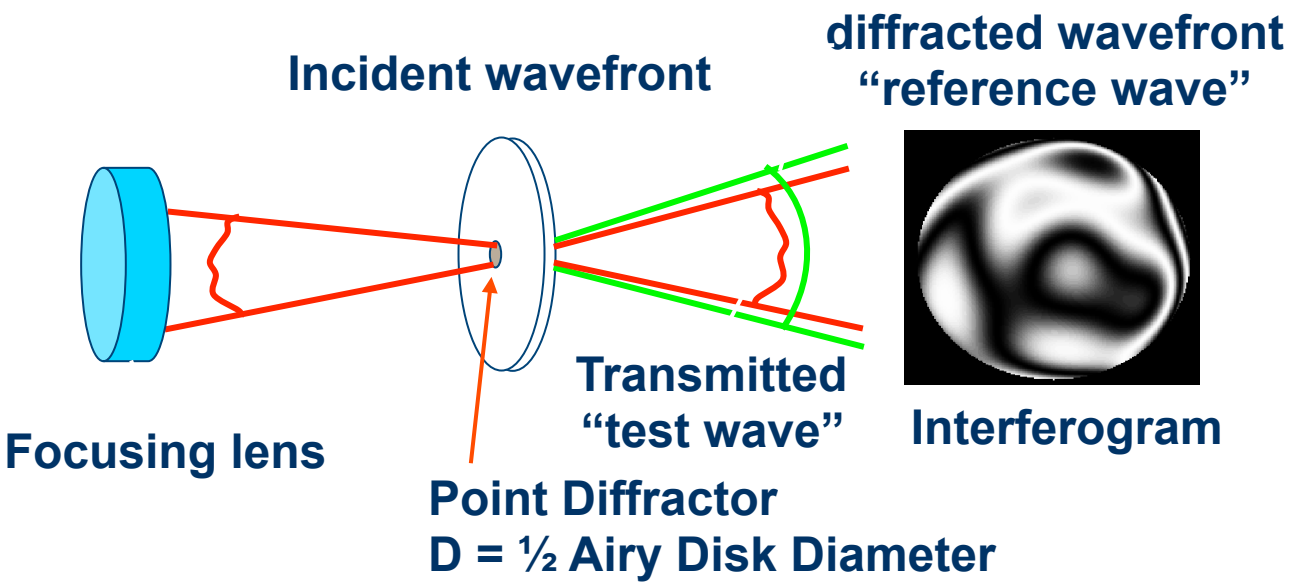
Scatterplate Interferometer



Ref: A.H. Shoemaker and M.V.R.K. Murty, Appl. Opt., 5, p. 603, 1966.

8.2.7 Smartt Point Diffraction Interferometer (PDI)

World's Simplest Interferometer



Generates "synthetic reference wave" from point diffracting element

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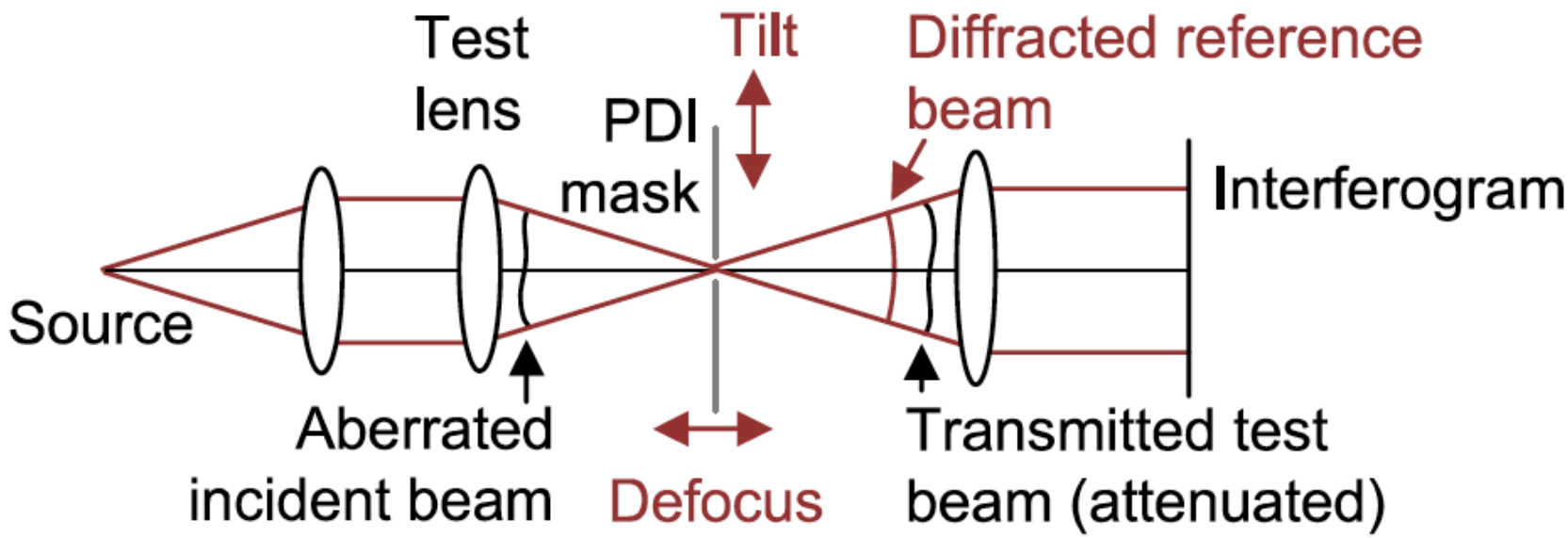
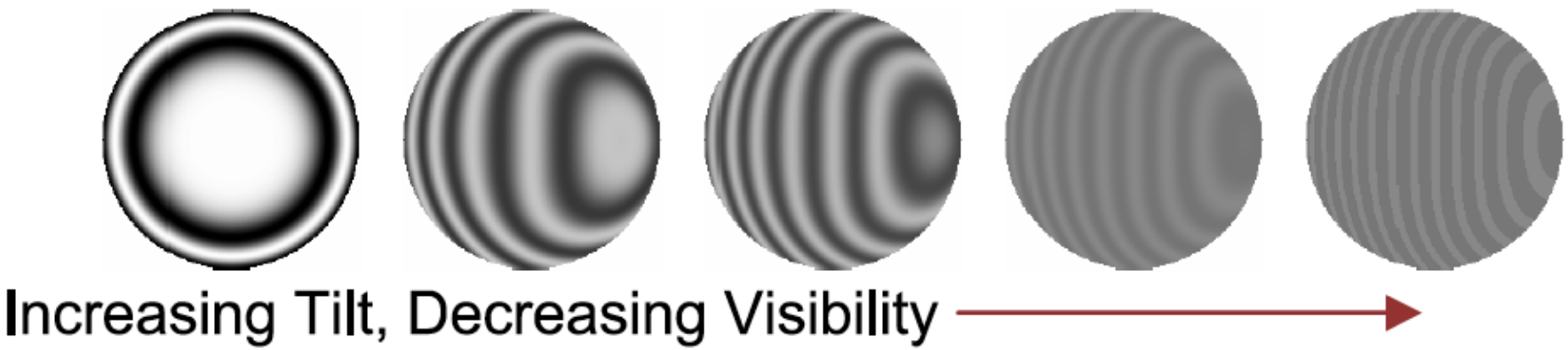
Changing Tilt and Defocus of PDI

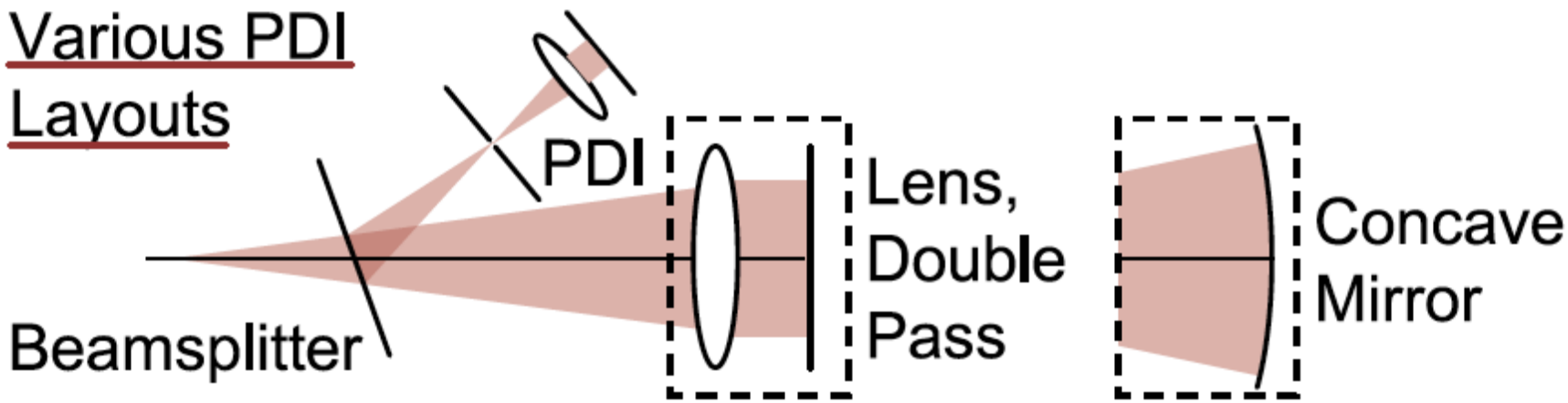


Changing Tilt Reduces Fringe Visibility



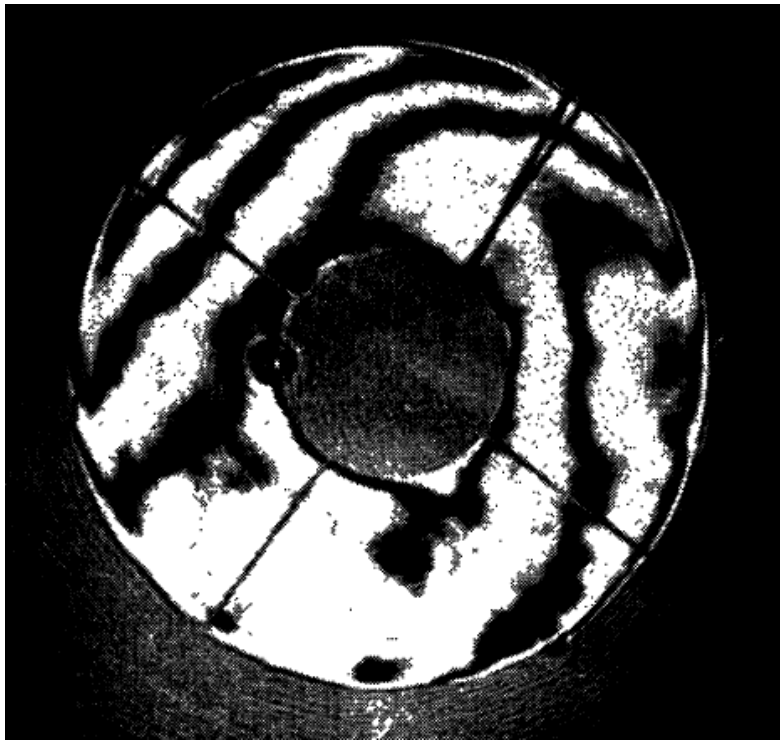
The major disadvantage of the PDI is that the amount of light in the reference beam depends on the position of the pinhole.

Other Testing Configurations

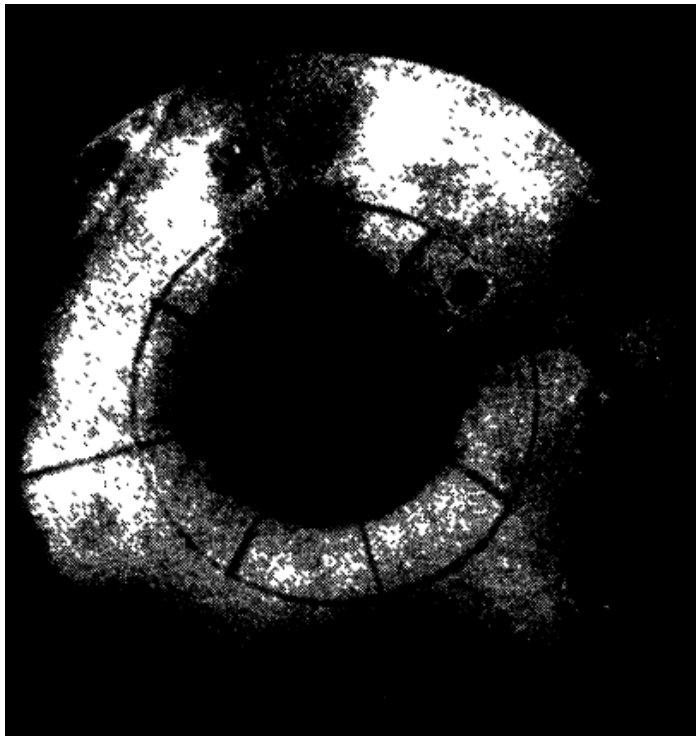


Place the PDI at the location where the source is imaged.

PDI Test Results



Interferogram of 0.6-m Cassegrain telescope with a laser source.



Interferogram of 1.5m Mount Palomar telescope with a star as source.

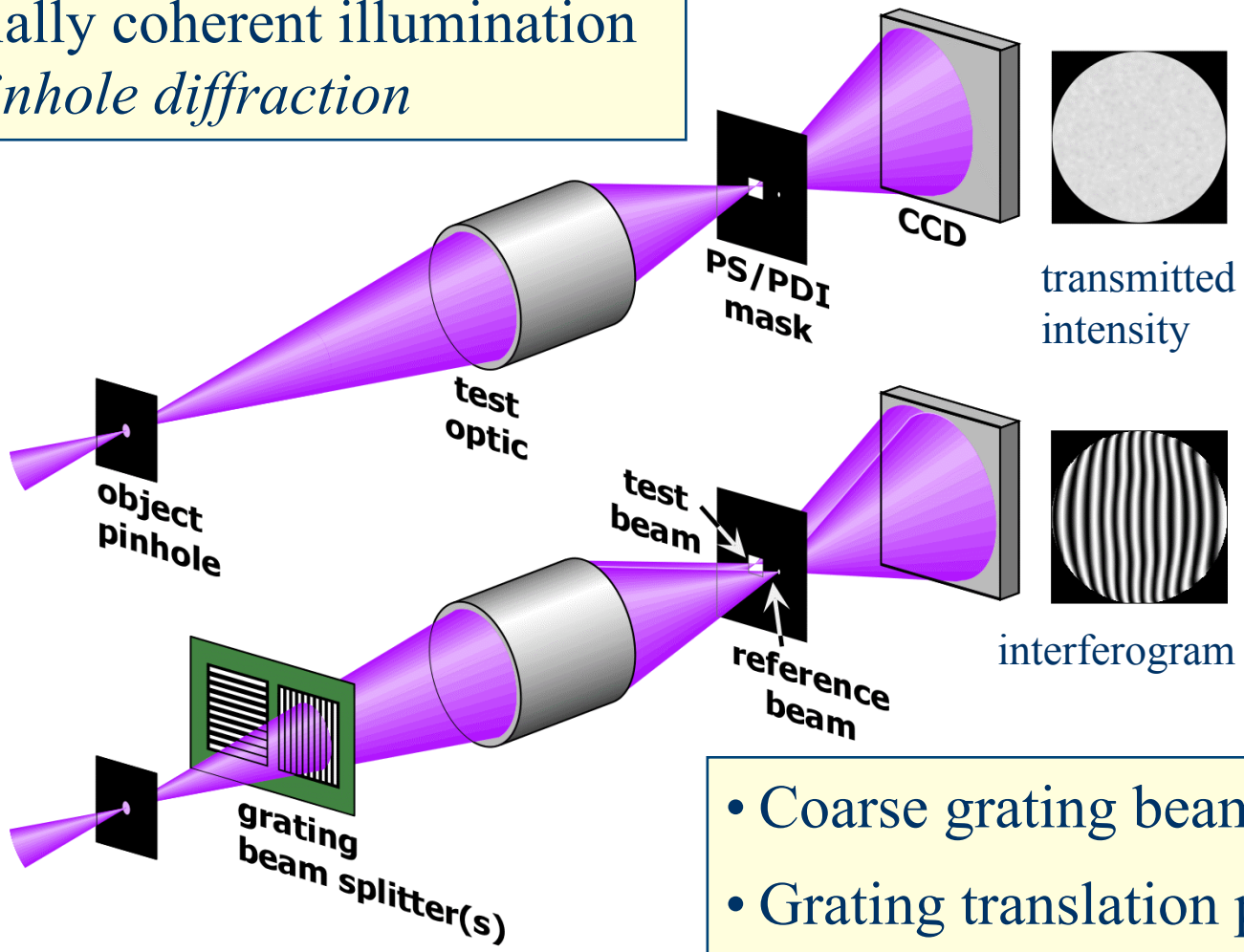
Ref: R. N. Smartt and W. H. Steel, Japan J. Appl. Phys. 14 (1975) Suppl. 14-1

How Do We Phase Shift?

- Two basic techniques
  - Use diffraction gratings
  - Use polarization techniques

Phase-Shifting Point Diffraction Interferometer (Modified Smartt Interferometer)

- Spatially coherent illumination by *pinhole diffraction*



- Coarse grating beam splitter
- Grating translation produces *phase-shifting*

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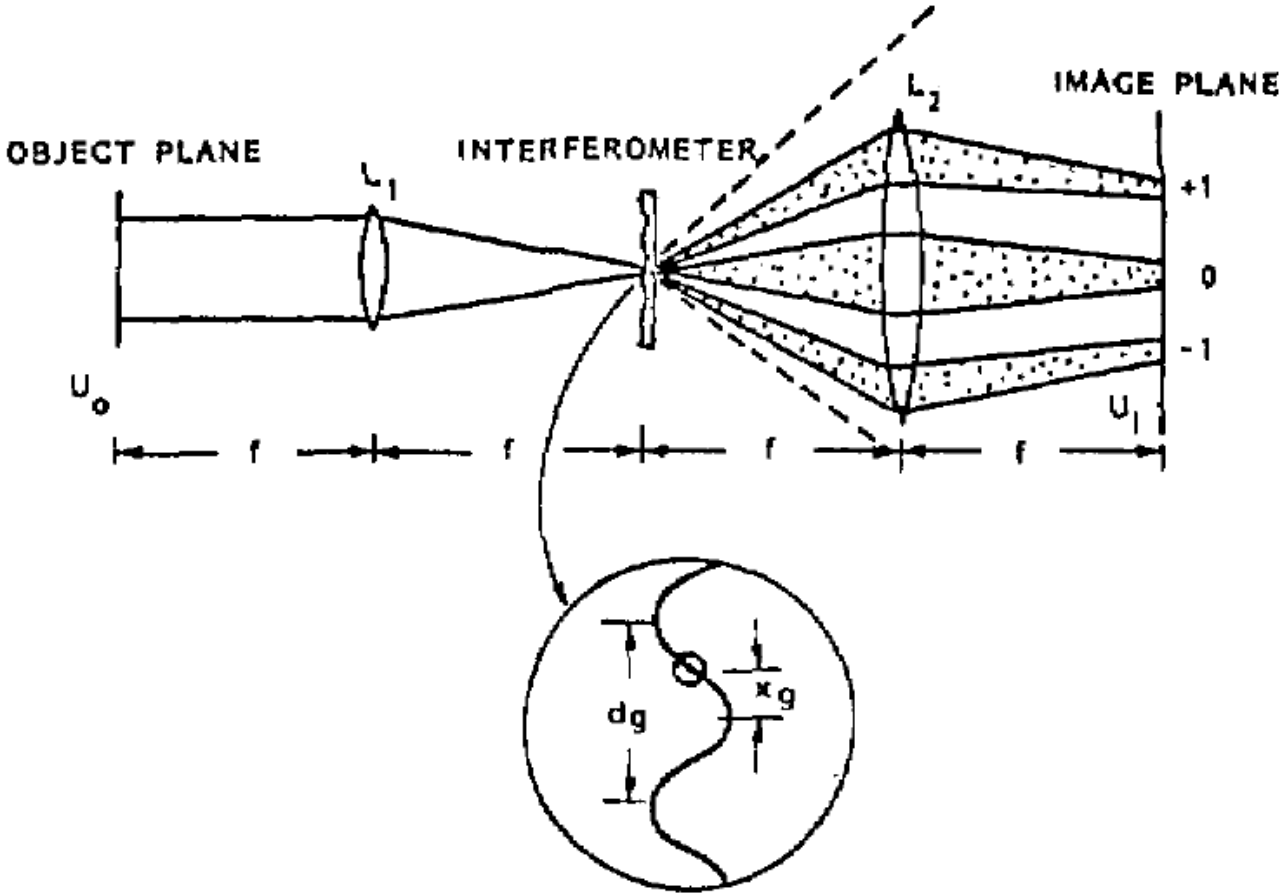
Ref: J. Bokor

Multichannel Phase-Shifted PDI



Ref: O. Kwon, Opt. Lett. 9 59 (1978)

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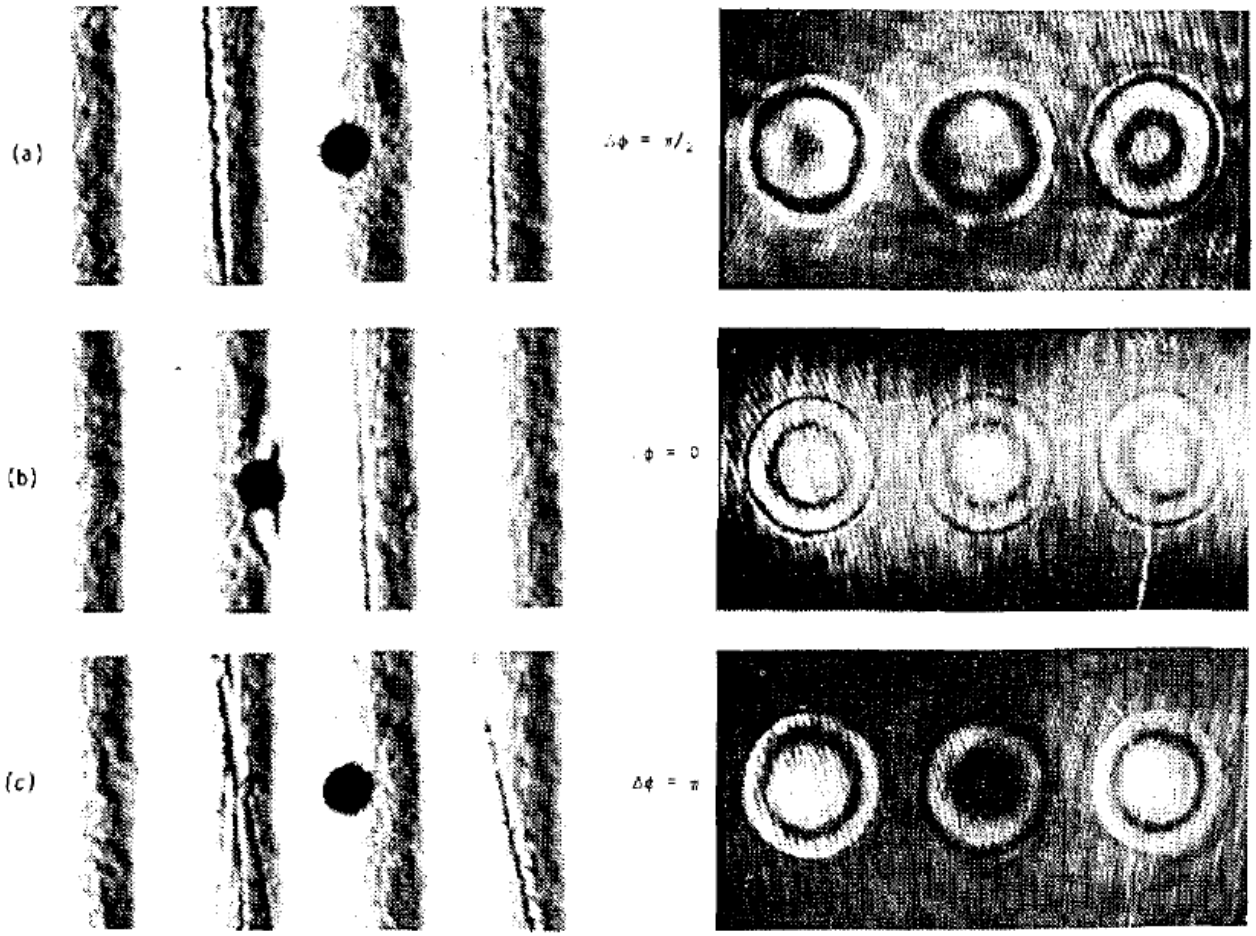
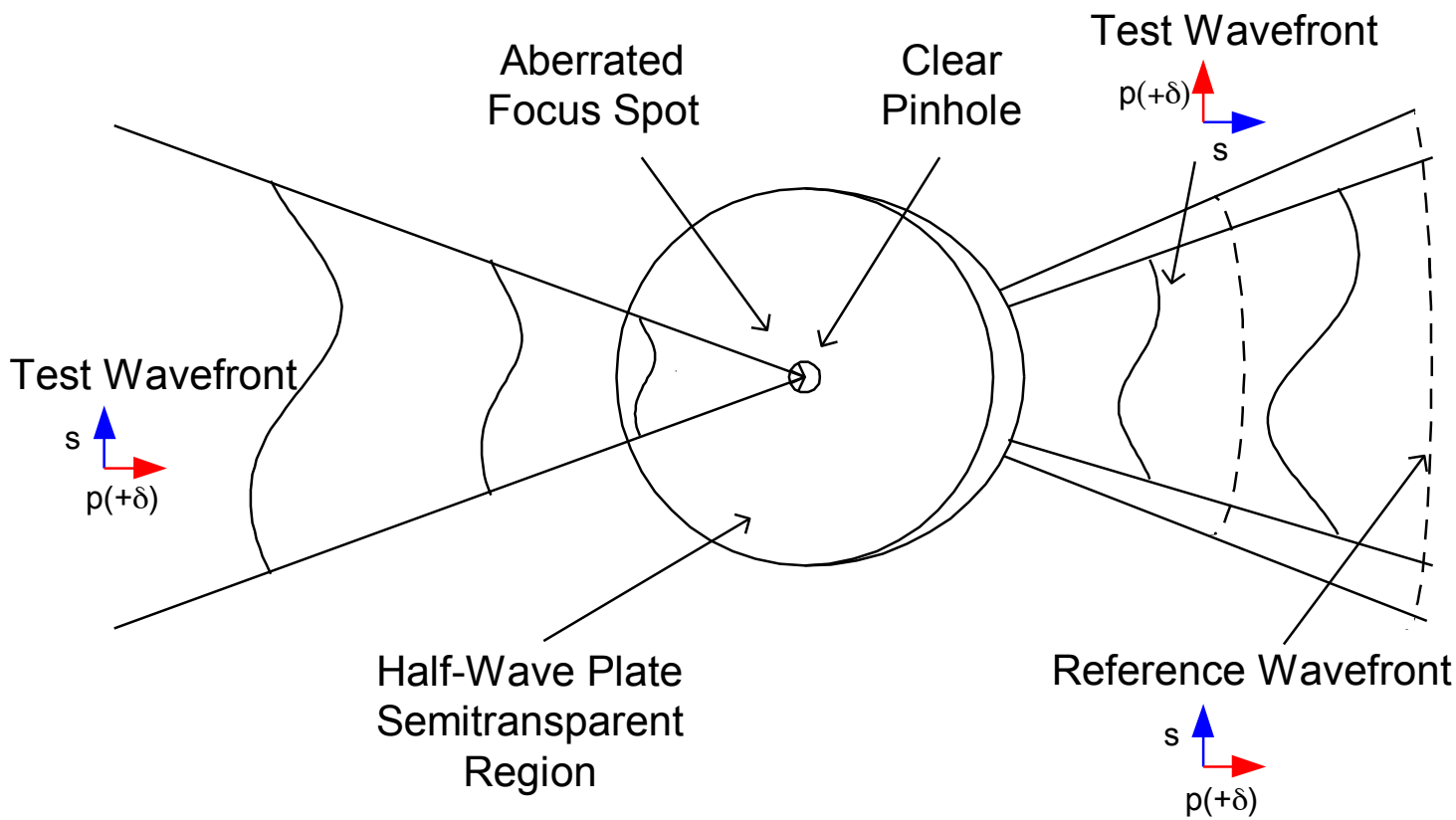
Measurement Results



Use of Half-Wave Plate PDI



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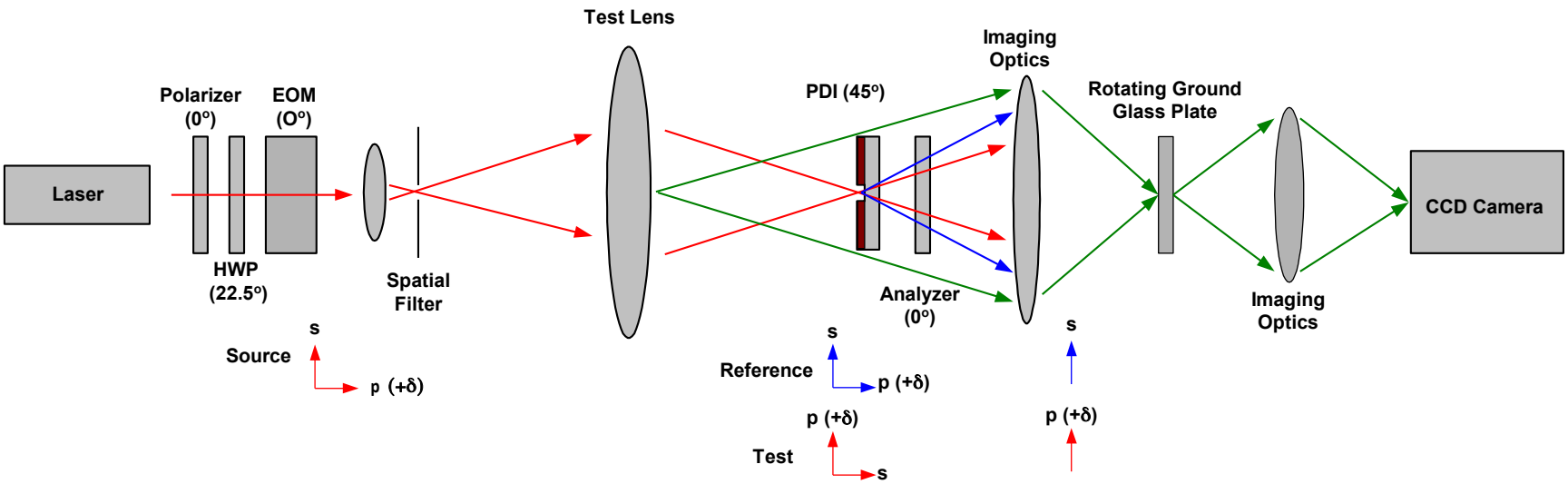
One Experimental Setup of Half-Wave Plate PDI



Ref: Robert M. Neal and James C. Wyant
APPLIED OPTICS, Vol. 45, page 3463, 20 May 2006

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Liquid-Crystal PDI

Plastic microsphere
in liquid crystal

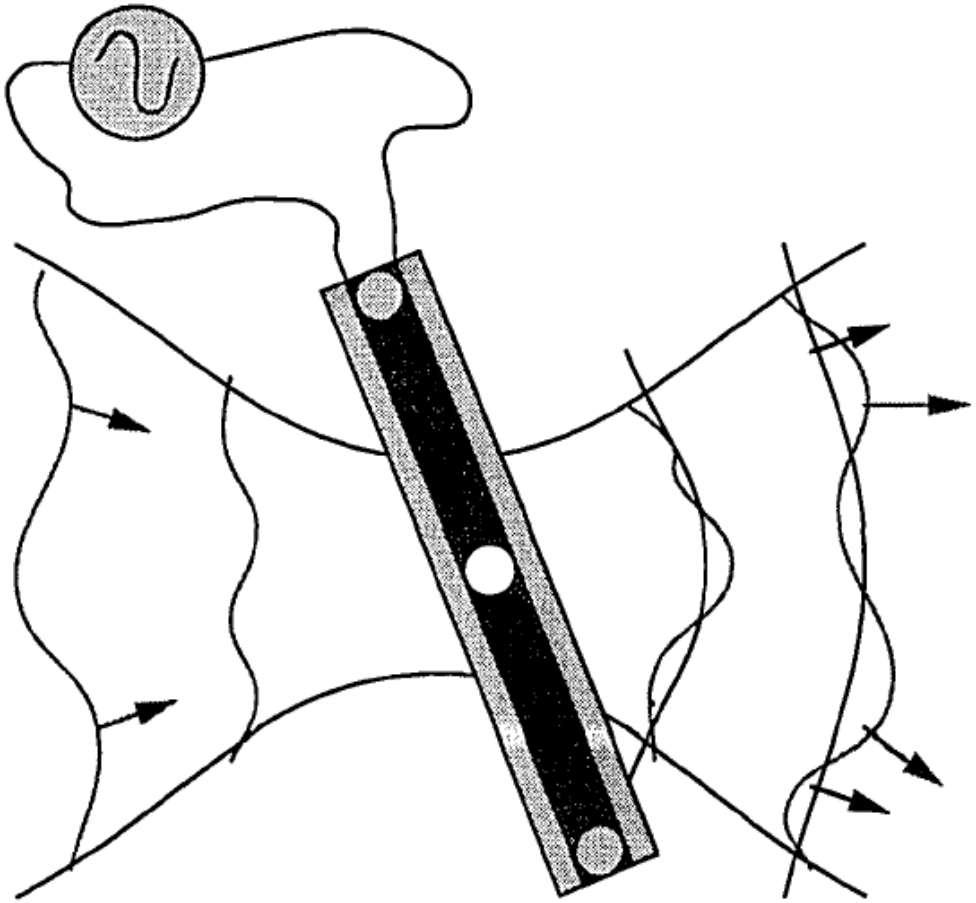
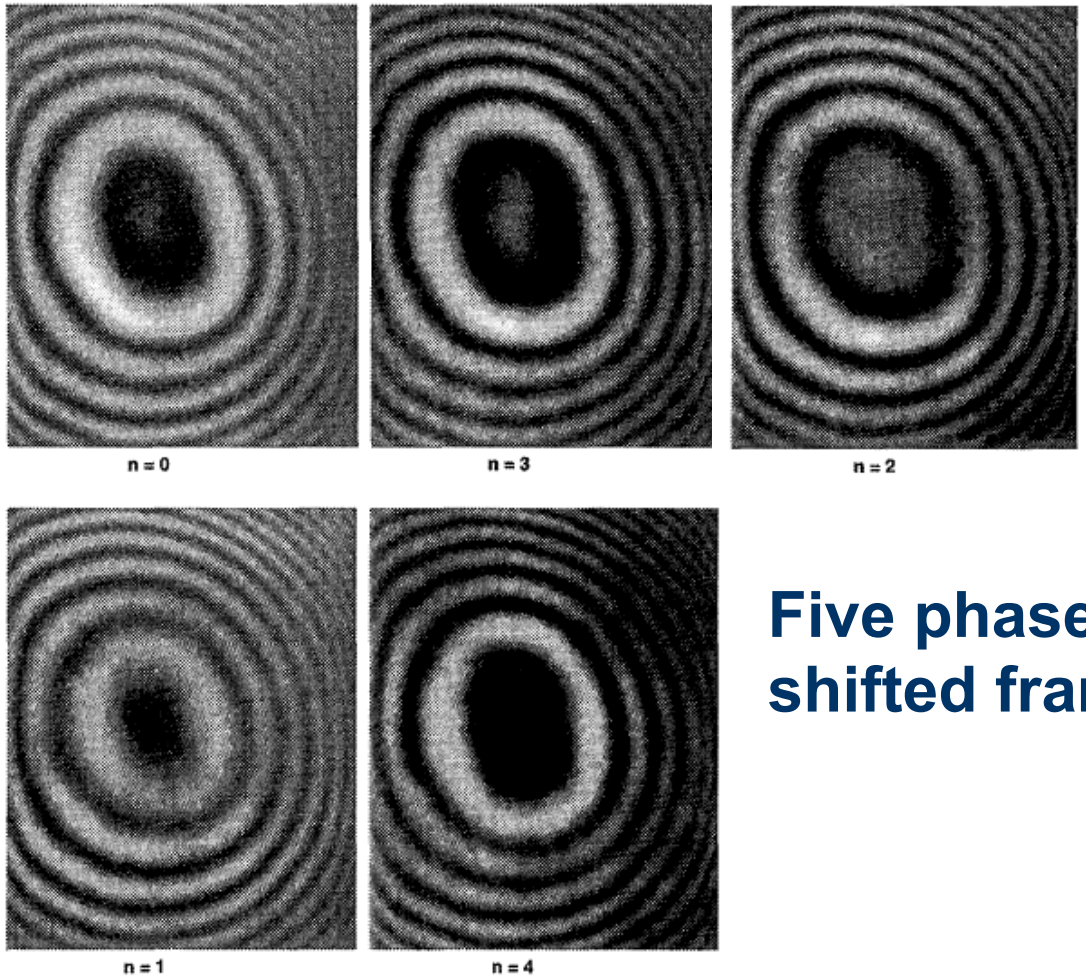


Fig. 1. Schematic of the LCPDI.

Test Results



Five phase shifted frames

Ref: C. Mercer and K. Creath, Opt. Lett. 19, 916 (1994)

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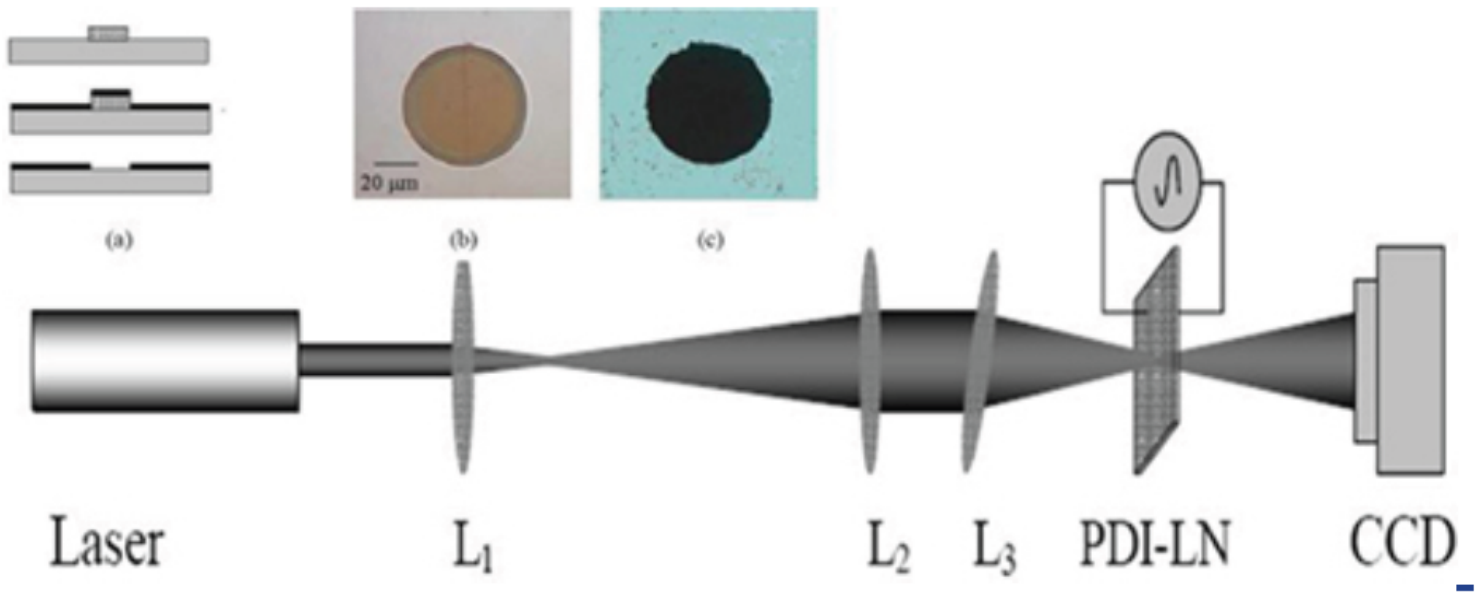
Lithium Niobate Crystal PDI



Pinhole etched in lithium niobate

Ref: P. Ferraro, M. Paturzo, and S. Grilli, 1 March 2007 SPIE Newsroom

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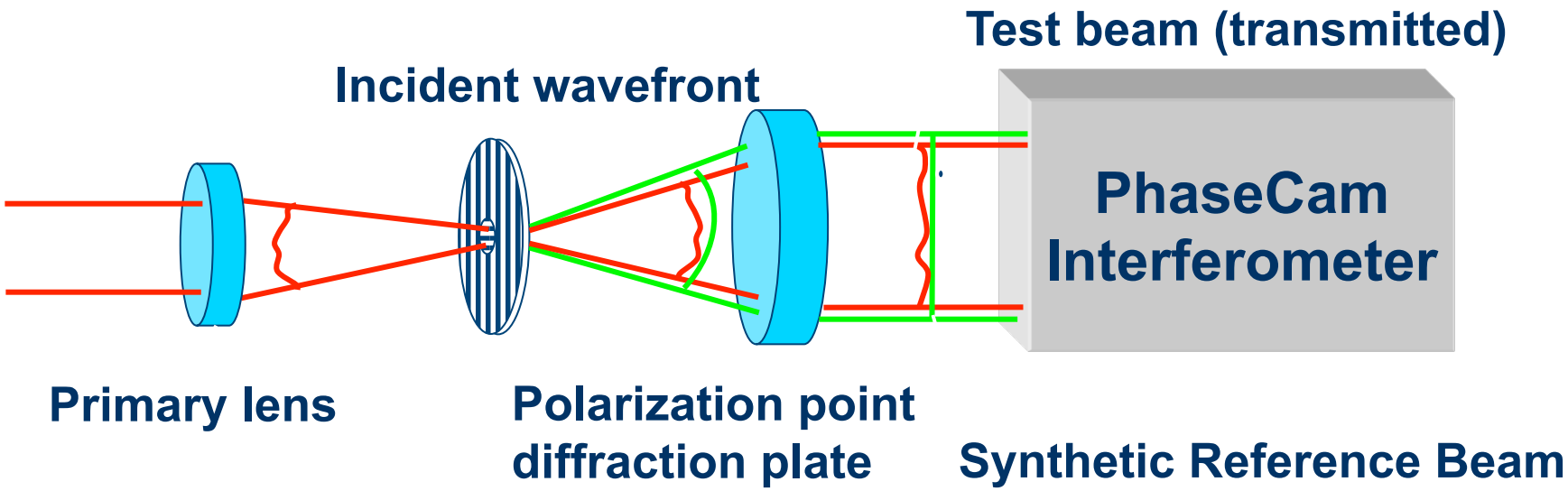
Instantaneous Phase-Shifting PDI



Synthetic reference wave is p-polarized
Transmitted test beam is s-polarized

Wavefront can be measured in a single shot!

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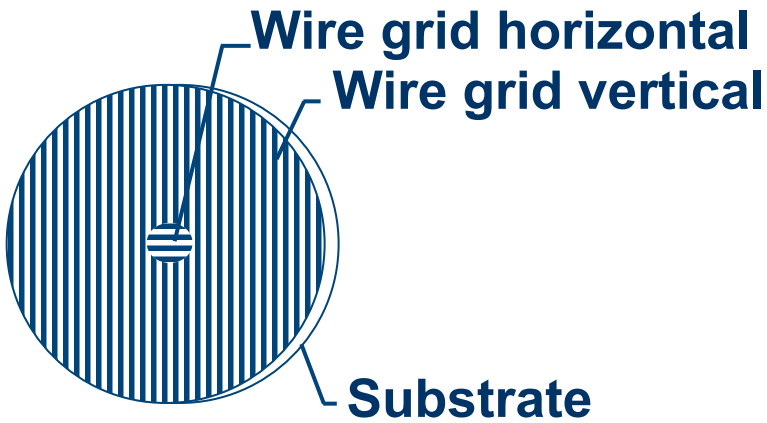
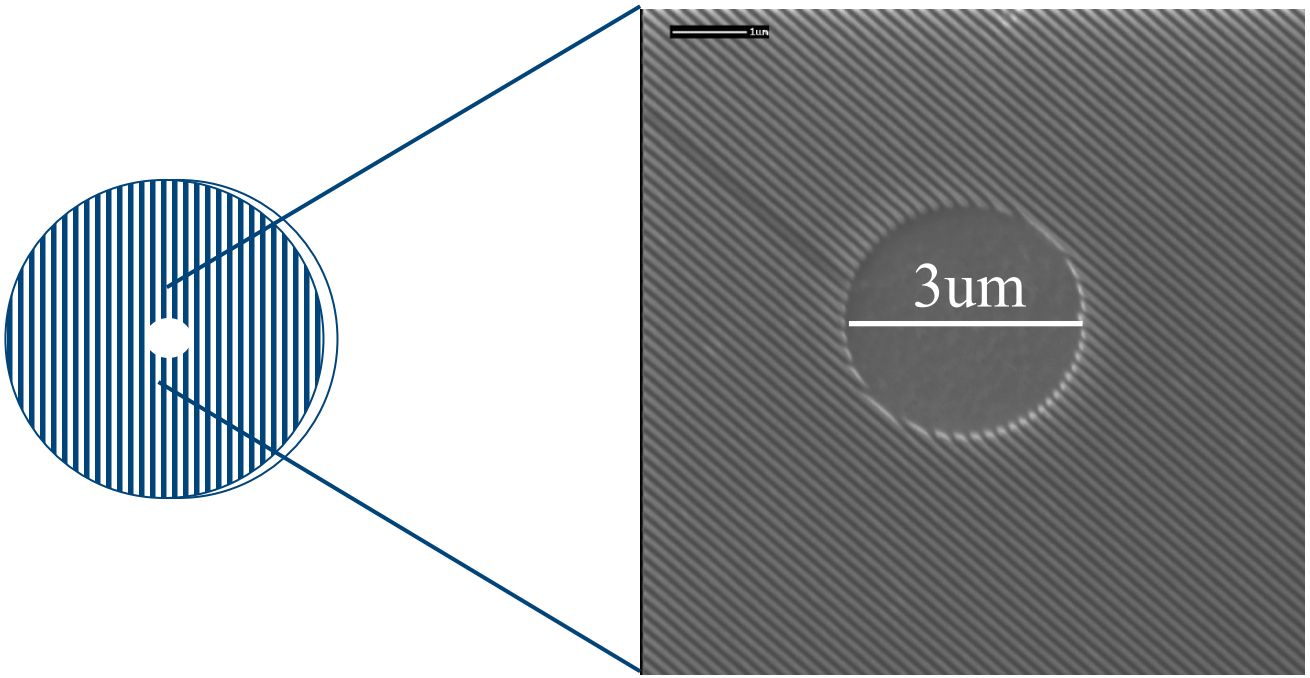
Polarization PDI Construction

Finite Conducting Grids
“wire grid polarizer”



Single Layer PDI Example



Focused Ion Beam Milling

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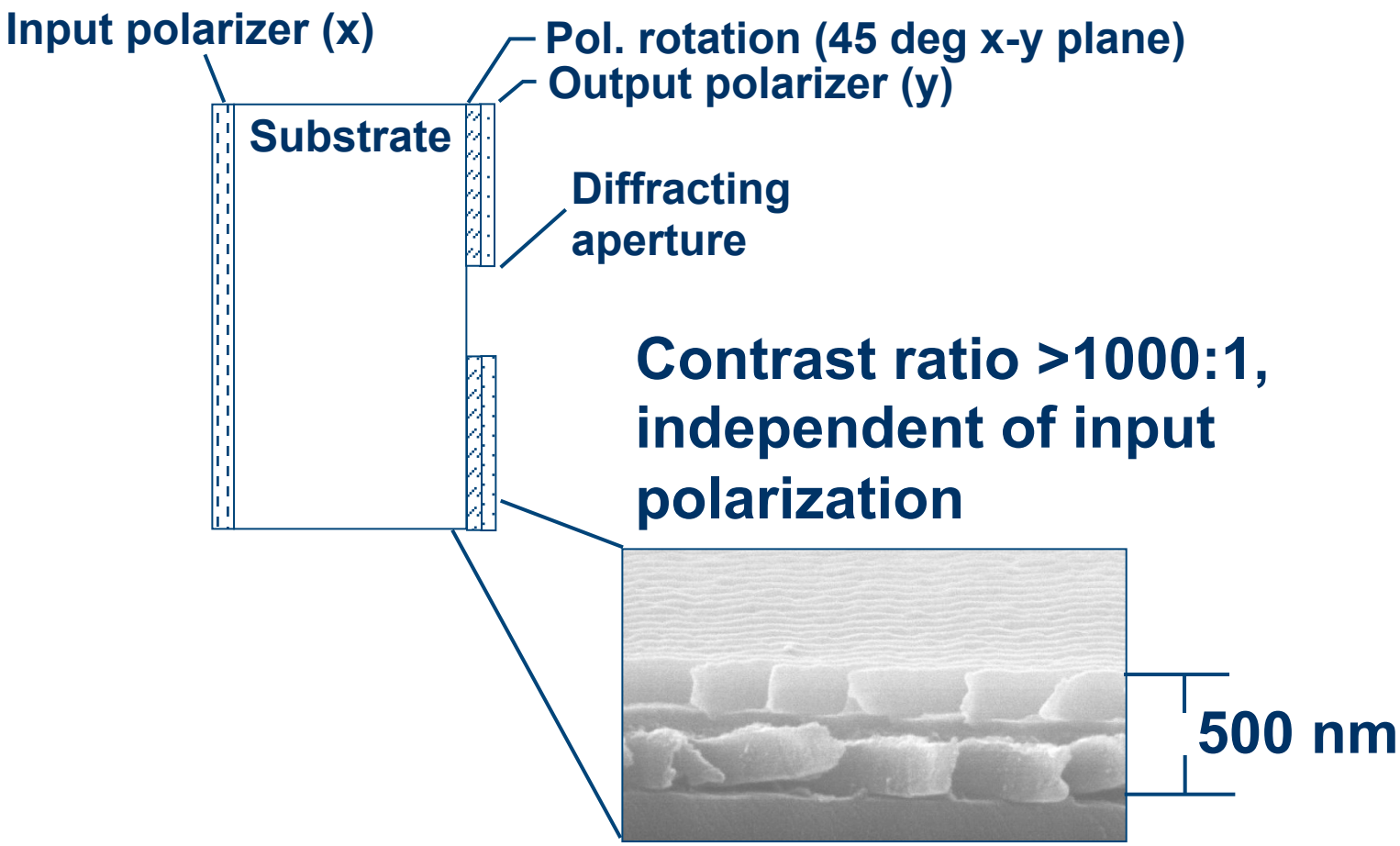
Polarization PDI Multilayer Design



Contrast ratio >1000:1, independent of input polarization

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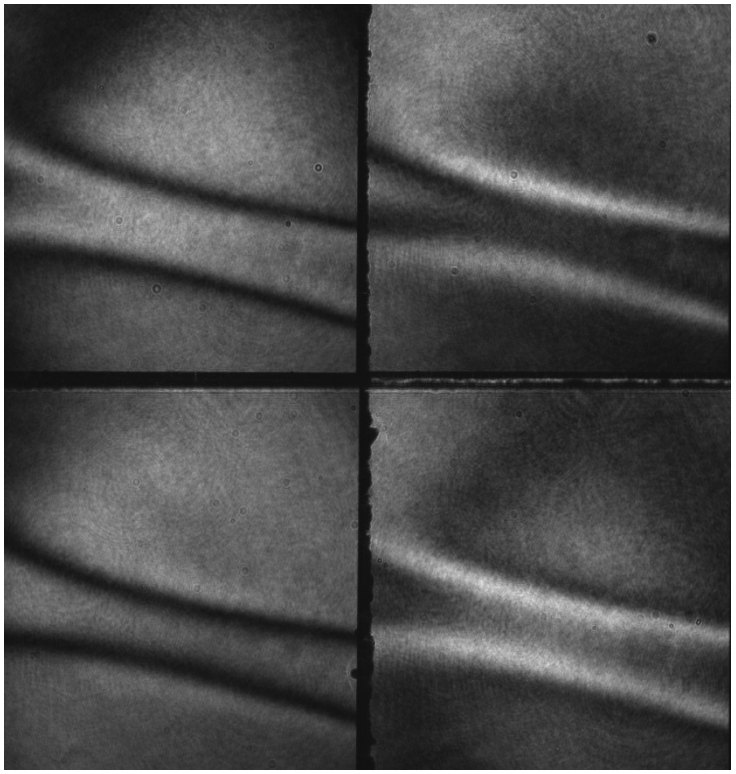
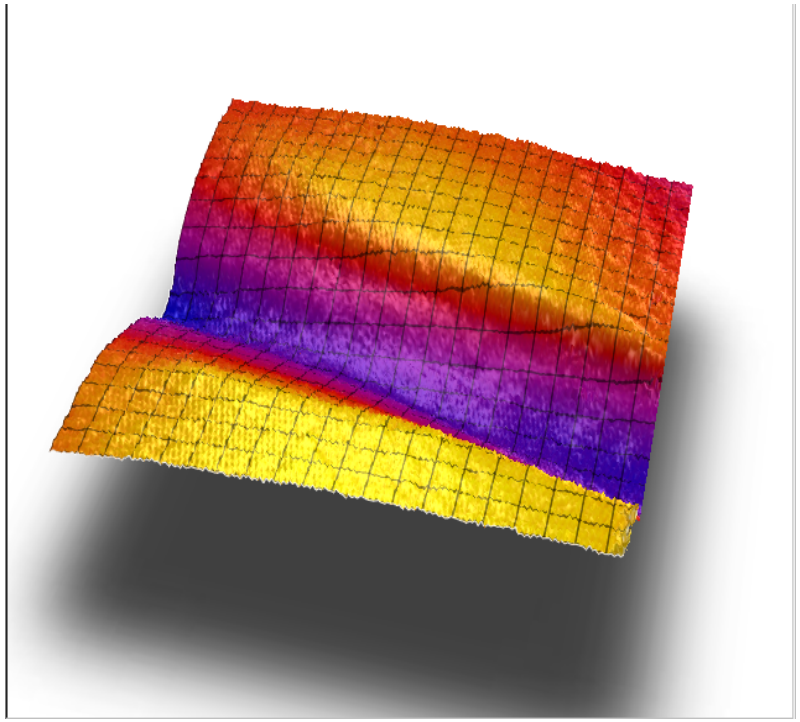
Air Flow Measurement





Simultaneous Interferograms **Phase Map**

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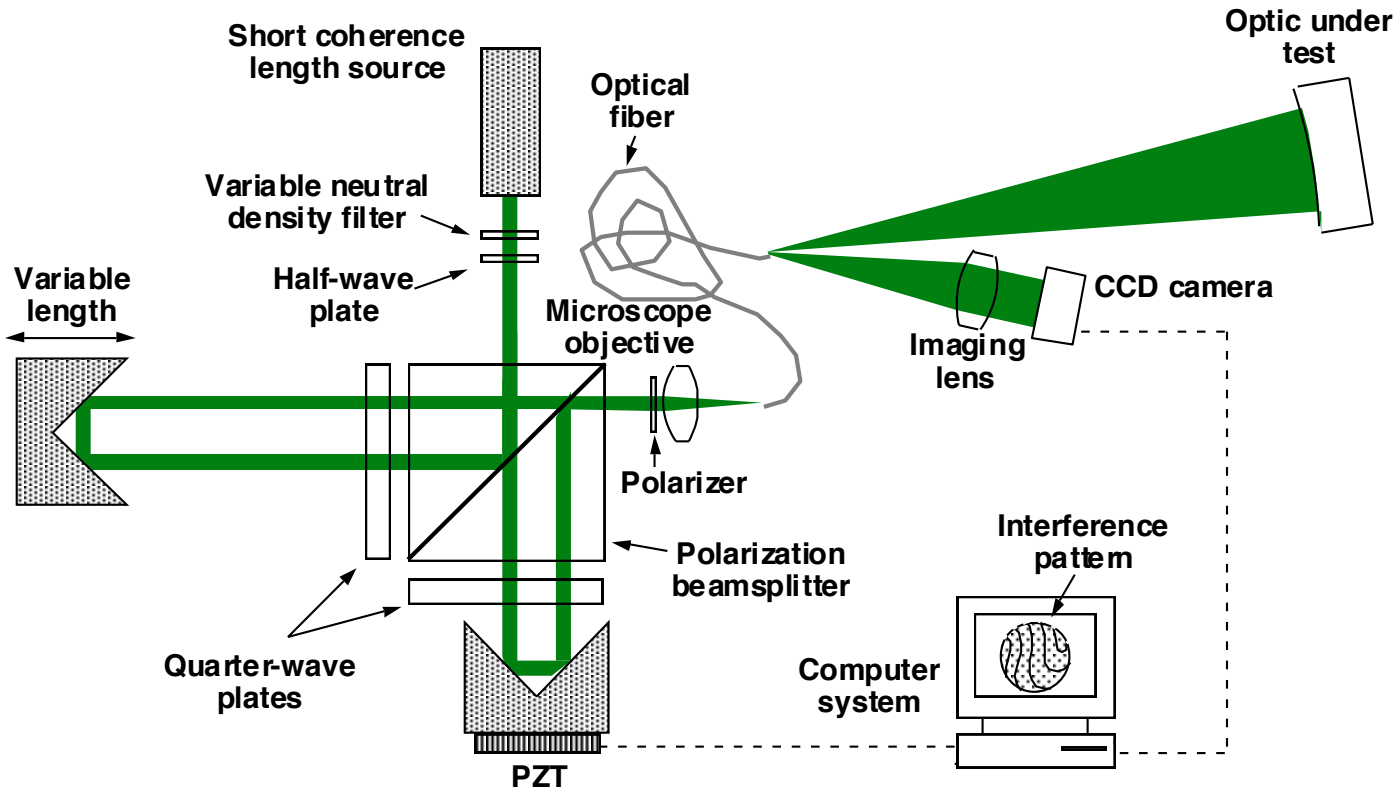
8.2.8 Sommargren Diffraction Interferometer



Phase Shifting Diffraction Interferometer (PSDI) configured to measure the surface figure of a concave off-axis aspheric mirror.

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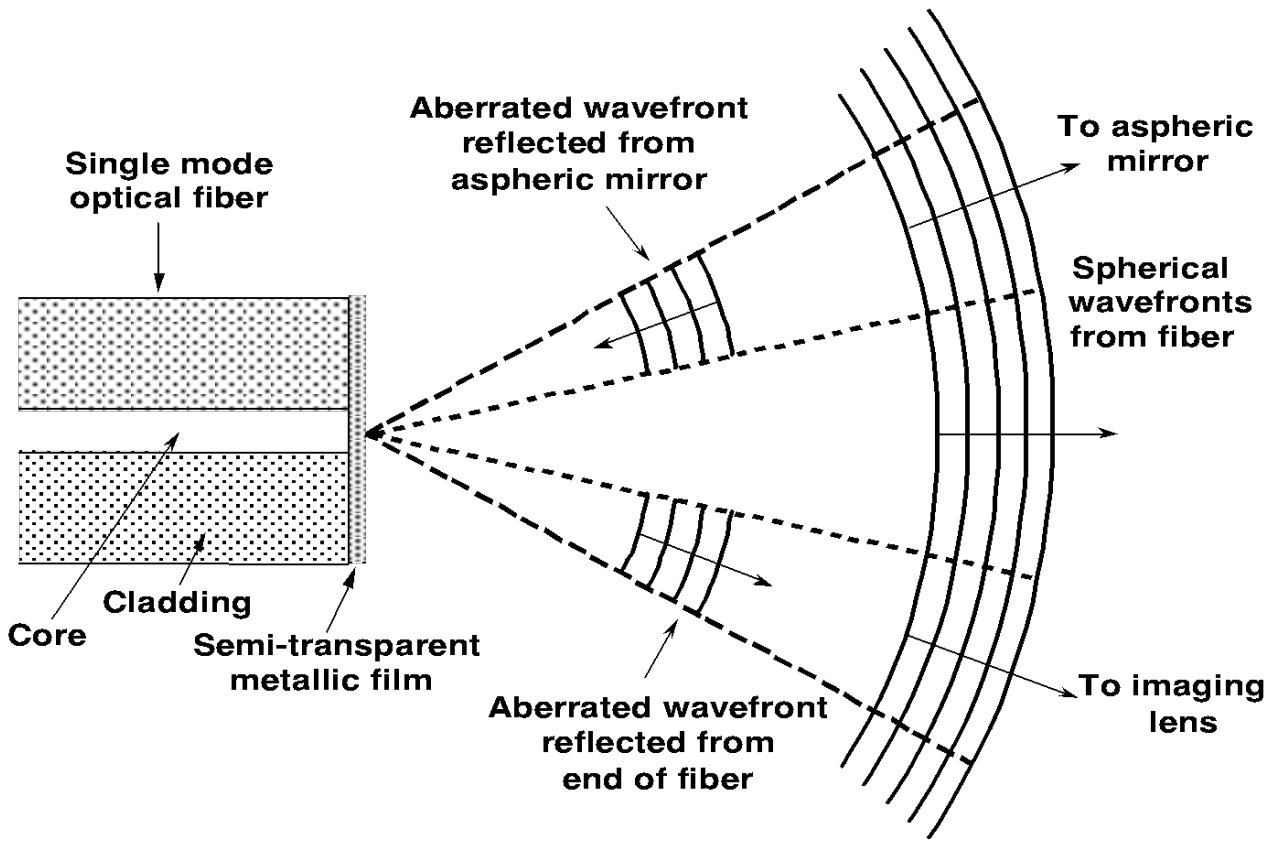
Detail of the Diffracted and Reflected Wavefronts at the End of the Fiber



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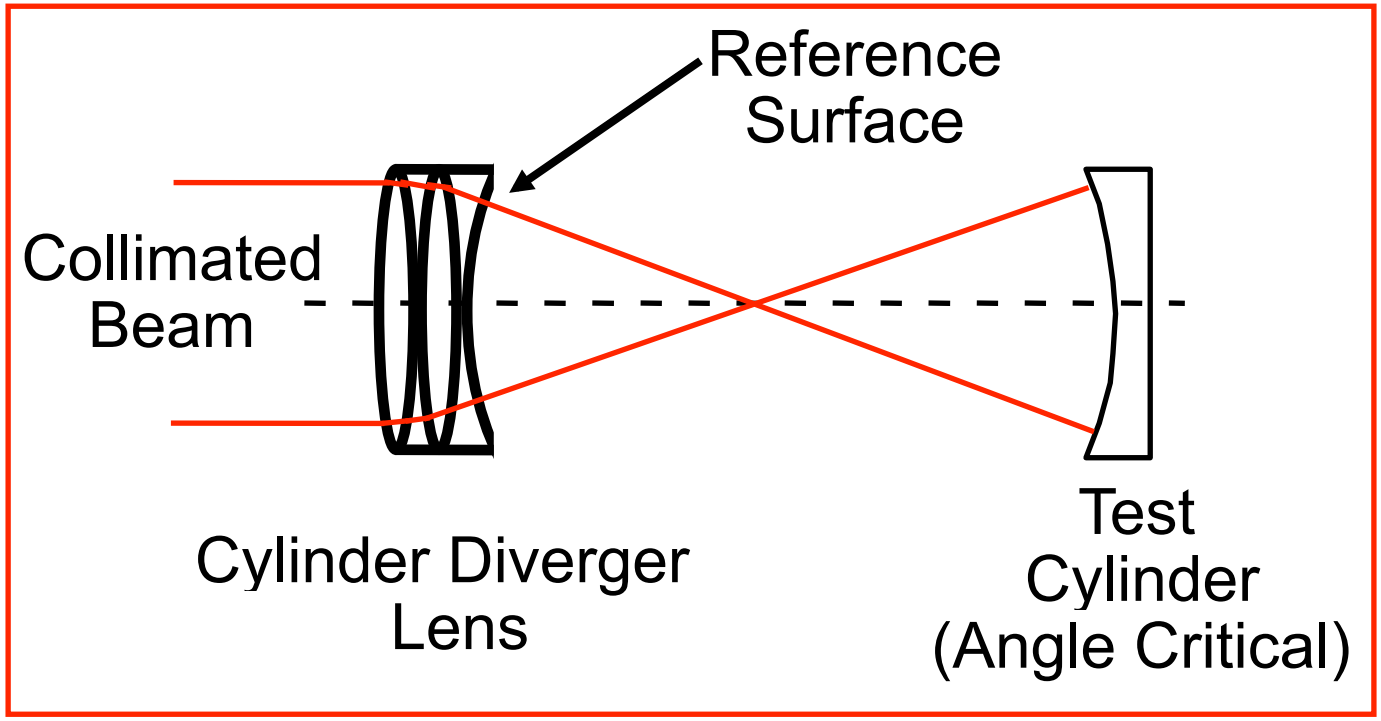
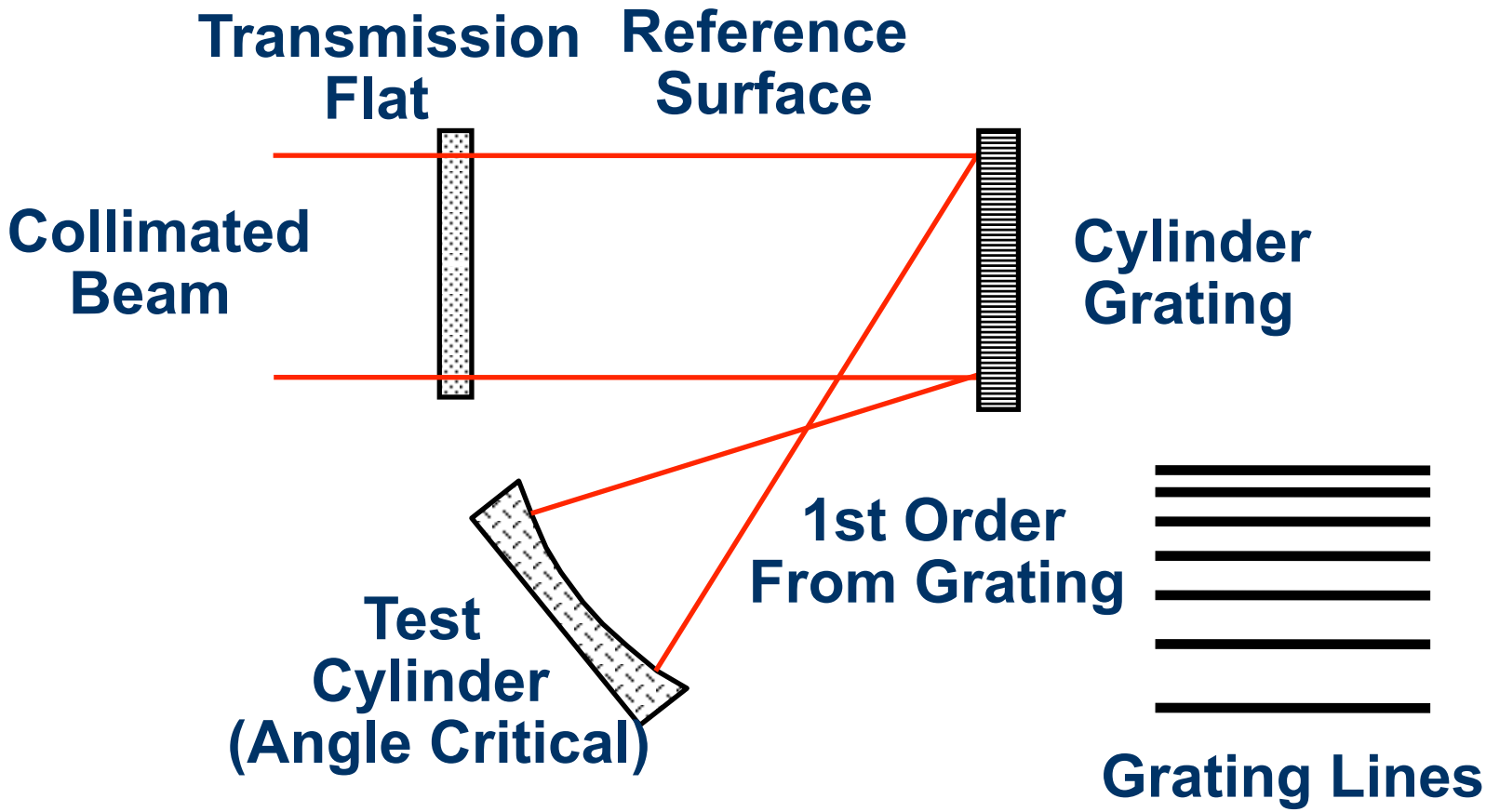
8.2.9 Measurement of Cylindrical Surfaces

- Need cylindrical wavefront
  - Reference grating: Off-axis cylinder
  - Cylinder null lens: Hard to make
- Direct measurement - No modifications to interferometer
- Concave and convex surfaces
- Quantitative - phase measurement

Cylinder Null Lens Test Setup



Cylinder Grating Test Setup



8.2.10 Long-Wavelength Interferometry

- Wavelengths of primary interest
- Test infrared transmitting optics
- Test optically rough surfaces

Wavelengths of Primary Interest

- 1.06 microns
  - Reduced sensitivity
- 10.6 microns
  - Reduced sensitivity
  - Test infrared transmitting optics
  - Testing optically rough surfaces

1.06 Micron Source Interferometer

- Diode Pumped Yag Laser
  Excellent coherence properties
- Normal Optics
- Normal CCD Camera

Conventional interferometry techniques work well.

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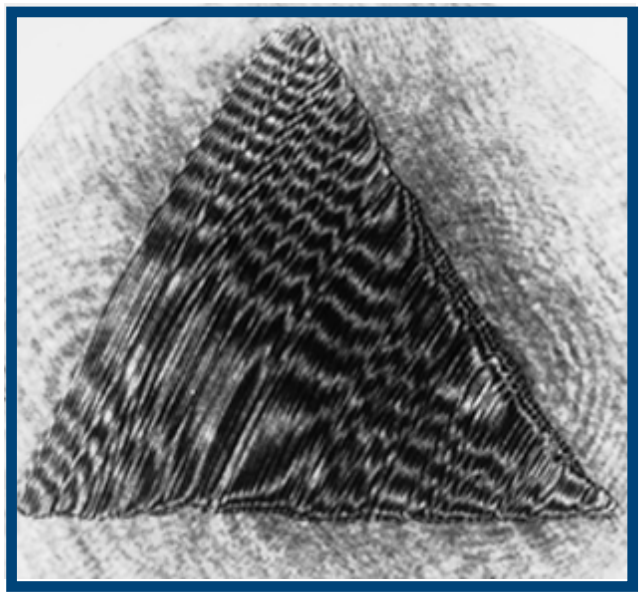
10.6 Micron Source Interferometer

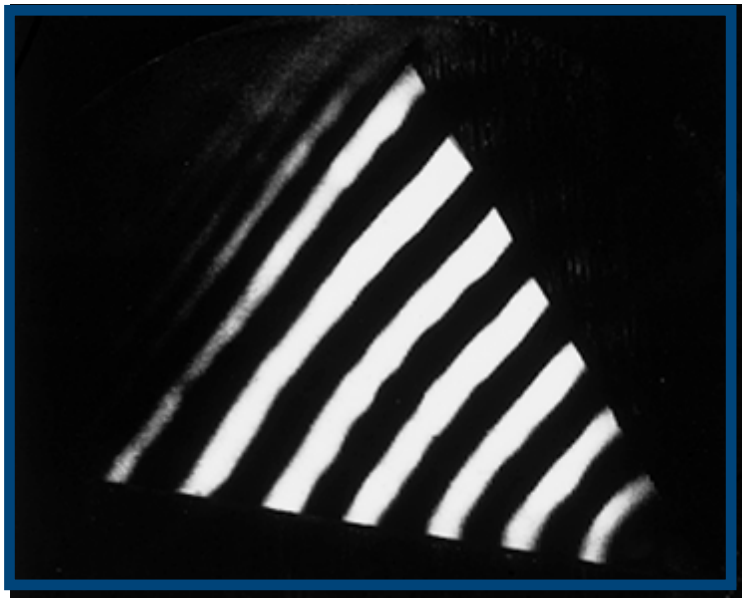
- Carbon Dioxide Laser
  Excellent coherence properties
- Zinc Selenide or Germanium Optics
- Bolometer

Conventional interferometry techniques work well.

Reduced Sensitivity Testing



0.633 microns wavelength



10.6 microns wavelength

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Testing Rough Surfaces

Assume surface height distribution is Gaussian with standard deviation σ.

The normal probability distribution for the height, h, is

$$\boxed{p(h) = \frac{1}{(2\pi)^{1/2}\sigma}\exp\left(-\frac{h^2}{2\sigma^2}\right)}$$

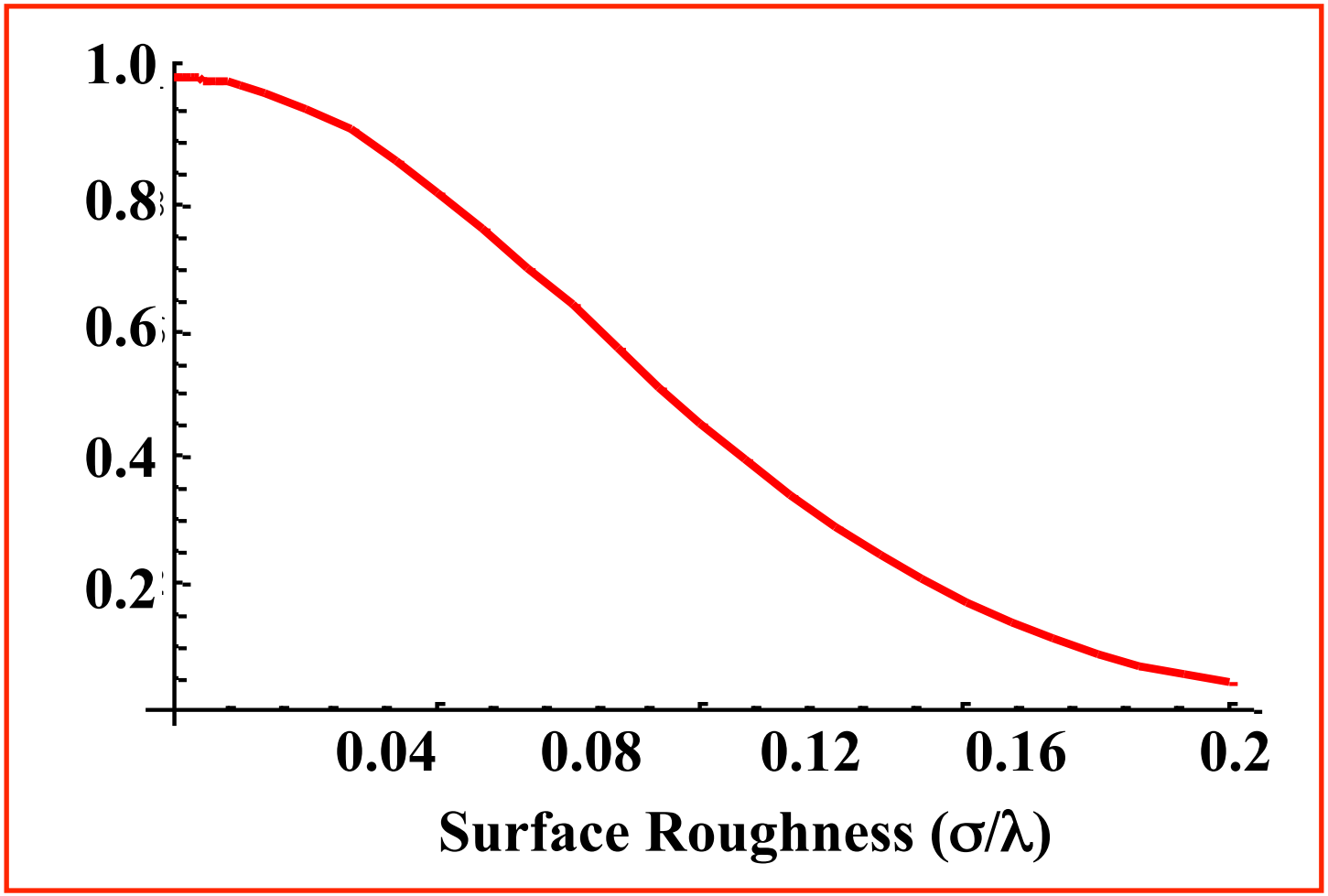
Fringe Contrast Reduction due to Surface Roughness

The fringe contrast reduction due to surface roughness is

$$C = \exp(-8\pi^2\sigma^2 / \lambda^2)$$

Reference: Appl. Opt. 11, 1862 (1980).

Fringe Contrast versus Surface Roughness - Theory



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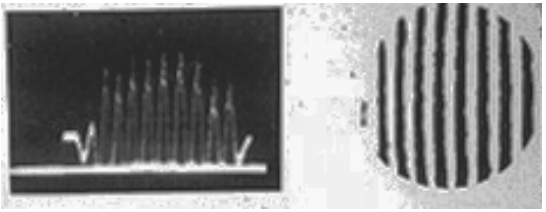
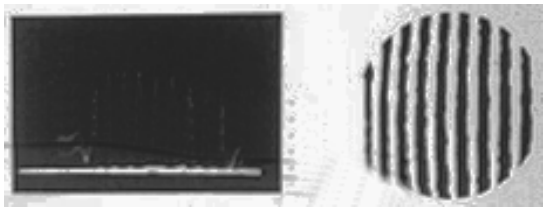
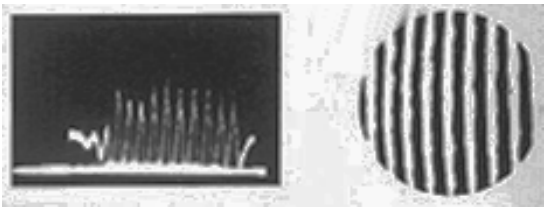
Interferograms Obtained for Different Roughness Surfaces



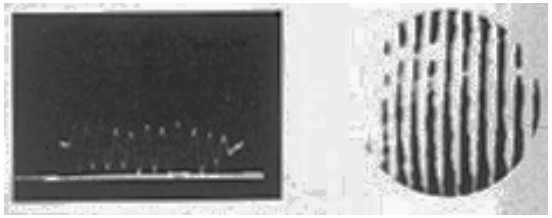
$\sigma = 0\ \mu m$, $C = 1.0$



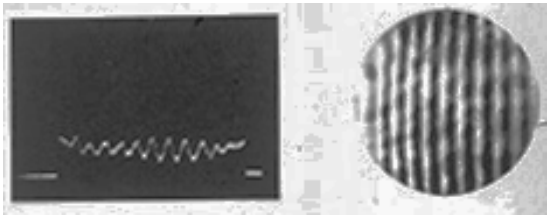
$\sigma = 0.32\ \mu m$, $C = 0.93$



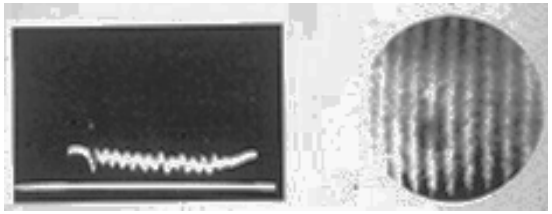
$\sigma = 0.44\ \mu m$, $C = 0.87$



$\sigma = 0.93\ \mu m$, $C = 0.54$



$\sigma = 1.44\ \mu m$, $C = 0.23$



$\sigma = 1.85\ \mu m$, $C = 0.07$

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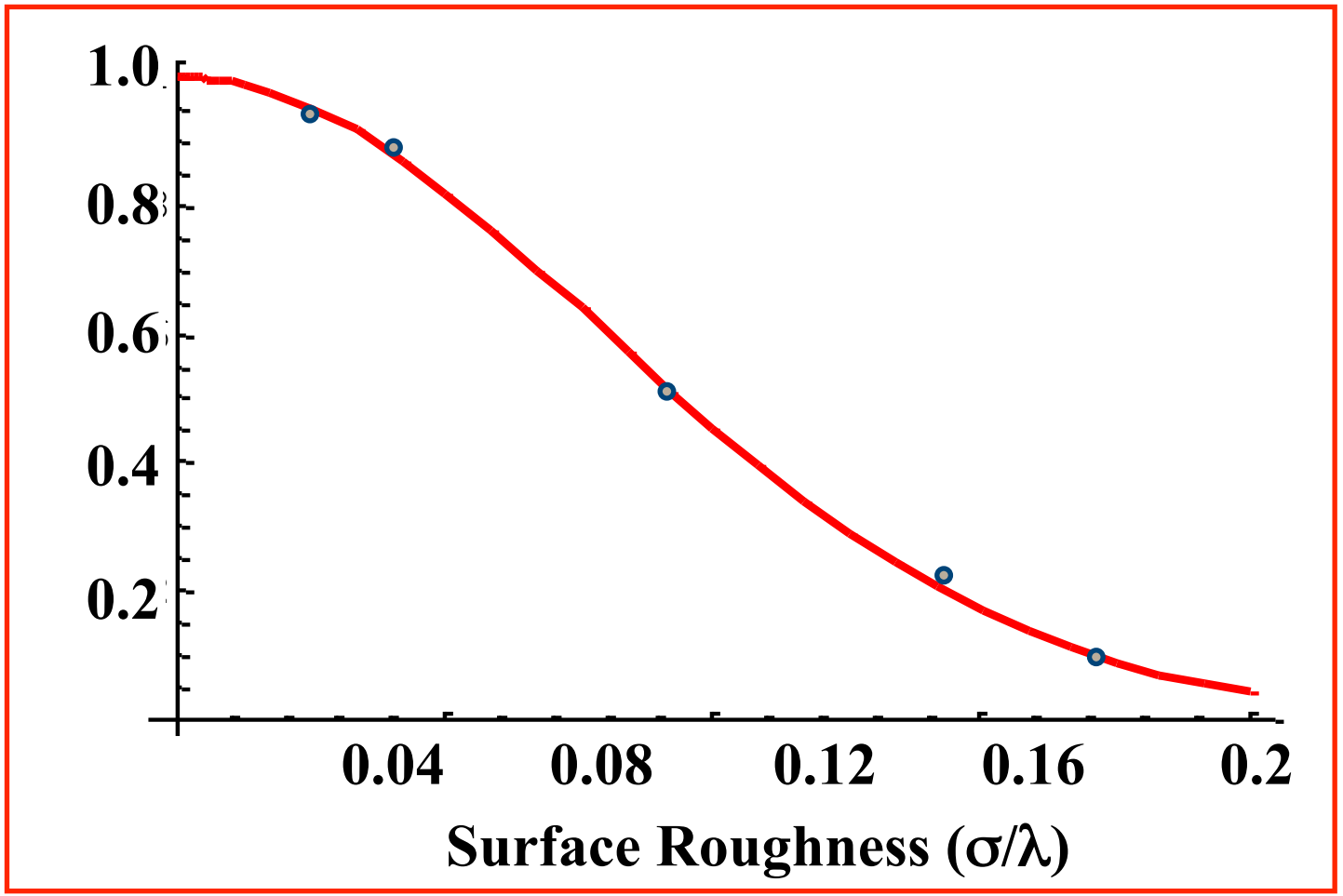
Fringe Contrast versus Surface Roughness - Theory and Experiment



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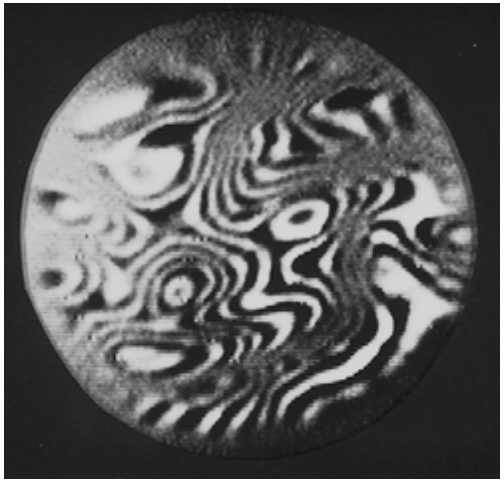
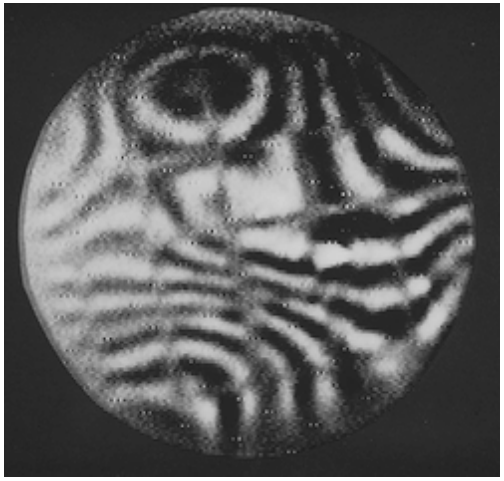
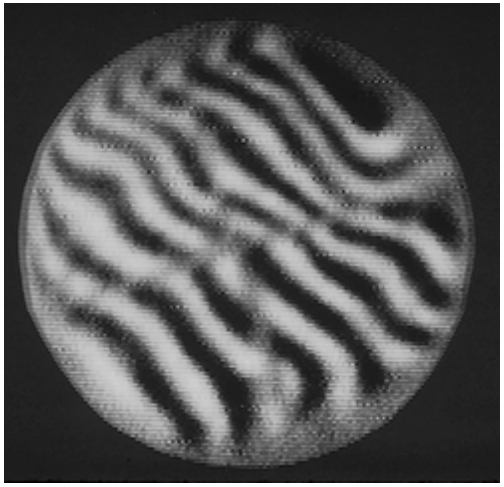
Infrared Interferograms of Off-Axis Parabolic Mirror in Chronological Order







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10.6 Micron Wavelength Interferometer

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