

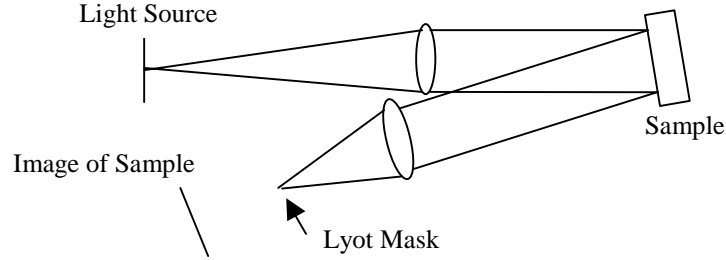
Measurement of Surface Quality

1. Lyot Test
2. FEEO
3. Nomarski Interferometer
4. Phase-Shifting Interference Microscope

Lyot Test (Zernike Phase Contrast)

Ref: Kingslake, Vol IV, p. 67

The figure below illustrates how the Lyot test, or as it is commonly called, the Zernike phase contrast test, can be used to measure surface roughness. If the sample is tested in reflection, the back surface is often coated to eliminate light from the second surface. The sample can also be tested in transmission.



The Lyot mask has an intensity transmittance of a^2 for the region within the first dark ring of the Airy disk focused on the mask and essentially 100% transmittance for the region outside the first dark ring of the Airy disk. The mask also retards the phase of the light falling within the first dark ring of the Airy disk 90° (positive contrast) or 270° (negative contrast). If $z(x,y)$, the height variation of the test sample surface, is a small fraction of a wavelength of the light used, the amplitude of the light reflected from the sample can be written as

$$e^{i\frac{2\pi}{\lambda}2z(x,y)} \approx 1 + \frac{2\pi}{\lambda}2z(x,y)i$$

For unit magnification and positive contrast the irradiance distribution, $I(x,y)$, in the image plane of the sample tested in reflection at normal incidence is given by

$$I(x,y) = t_o^2 \left| ai + \frac{4\pi}{\lambda} z(x,y)i \right|^2 = t_o^2 a^2 \left[1 + \frac{4\pi}{\lambda} \frac{z(x,y)}{a} \right]^2 \approx t_o^2 a^2 \left[1 + \frac{8\pi}{\lambda} \frac{z(x,y)}{a} \right]$$

where $t_o^2 a^2$ is the observed irradiance for a perfectly flat surface. Therefore, if $4\pi z(x,y)/\lambda \ll a$, the irradiance is linearly related to the height variations of the surface. To increase the resolution and the amount of light, the light source and mask are often annular.

As an example let $z = 10$ Angstroms and $\lambda = 633$ nm. Density, D , is defined as

$$D = \log \left[\frac{1}{a^2} \right]$$

D	0	0.5	1	1.5	2
a	1	0.56	0.32	0.18	0.10
$1 + \frac{8\pi}{\lambda} \frac{z(x,y)}{a}$	1.04	1.07	1.13	1.22	1.40
$\left[1 + \frac{4\pi}{\lambda} \frac{z(x,y)}{a}\right]^2$	1.04	1.07	1.13	1.24	1.44

Figure 1 shows a diagram of a typical phase-contrast microscope.

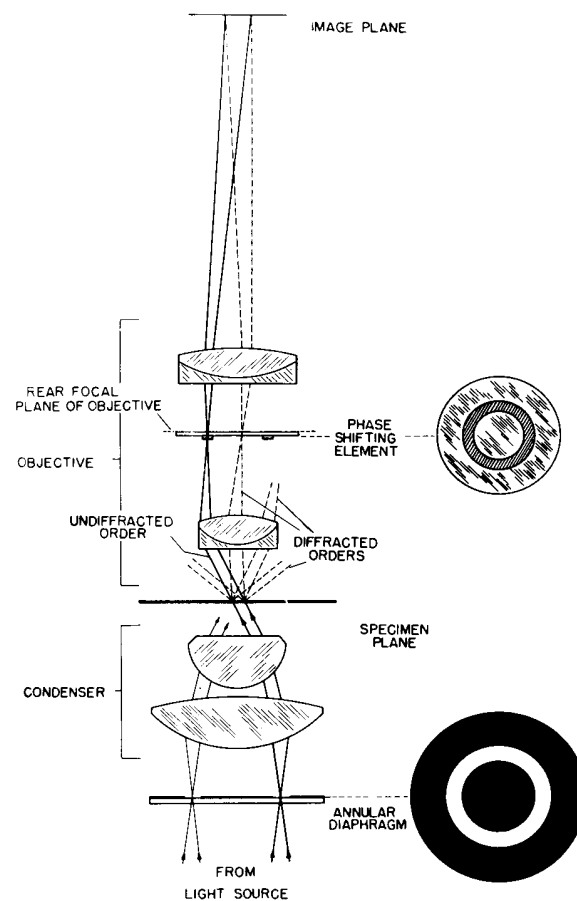


Figure 1. Phase-contrast microscope (ref: R. Kingslake, “Applied Optics and Optical Engineering”, Vol. IV, p. 68, (1967)).

The following three results obtained using the Zernike phase contrast (Lyot test) are from the “Atlas of Optical Phenomena”, Vol. 1 by Cagnet, Francon, and Thierri.

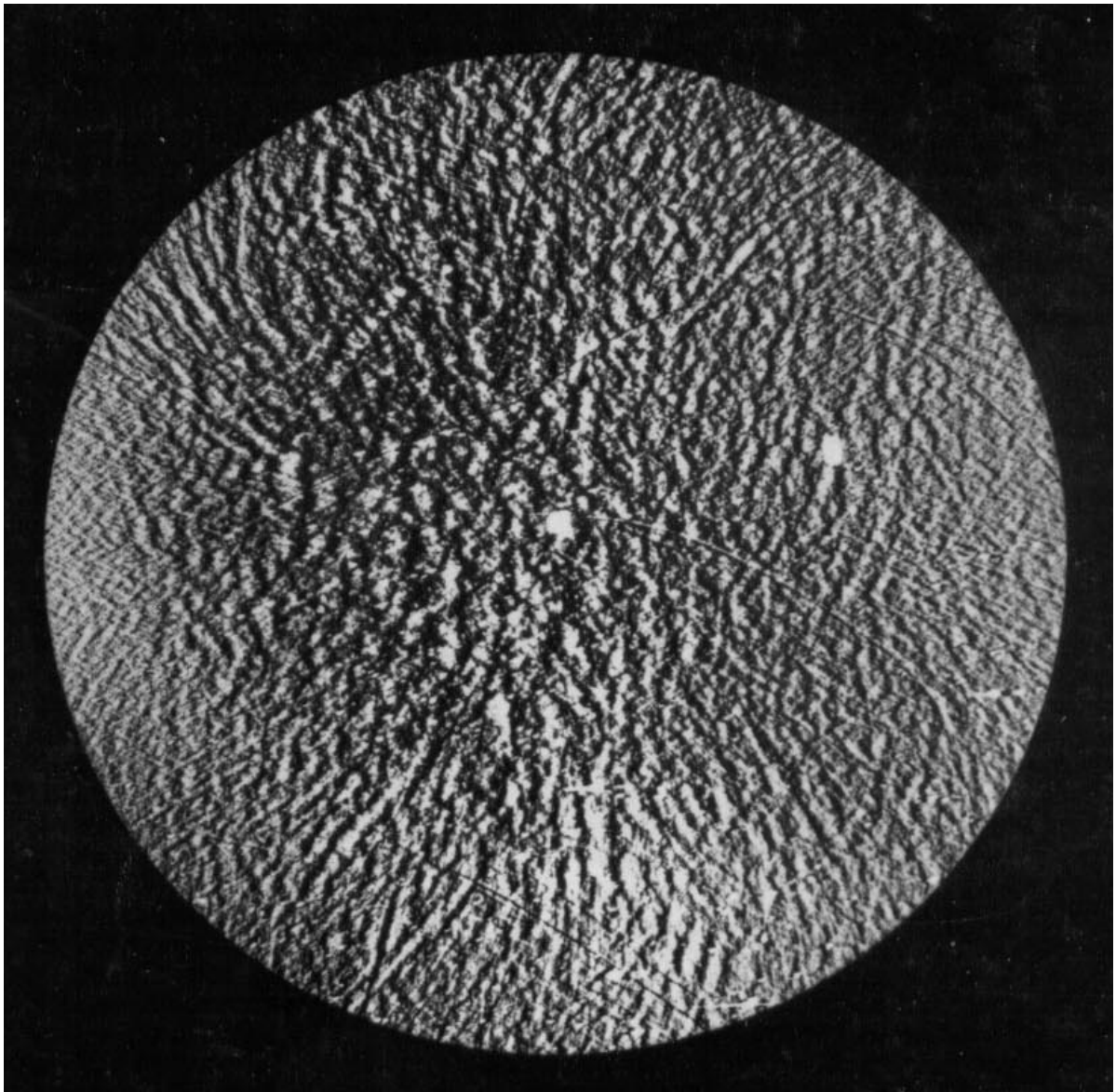


Figure 2. A pitch polished lens surface.

For the following two results the phase mask is made opaque. In this case the measurement method is called the Schlieren method.

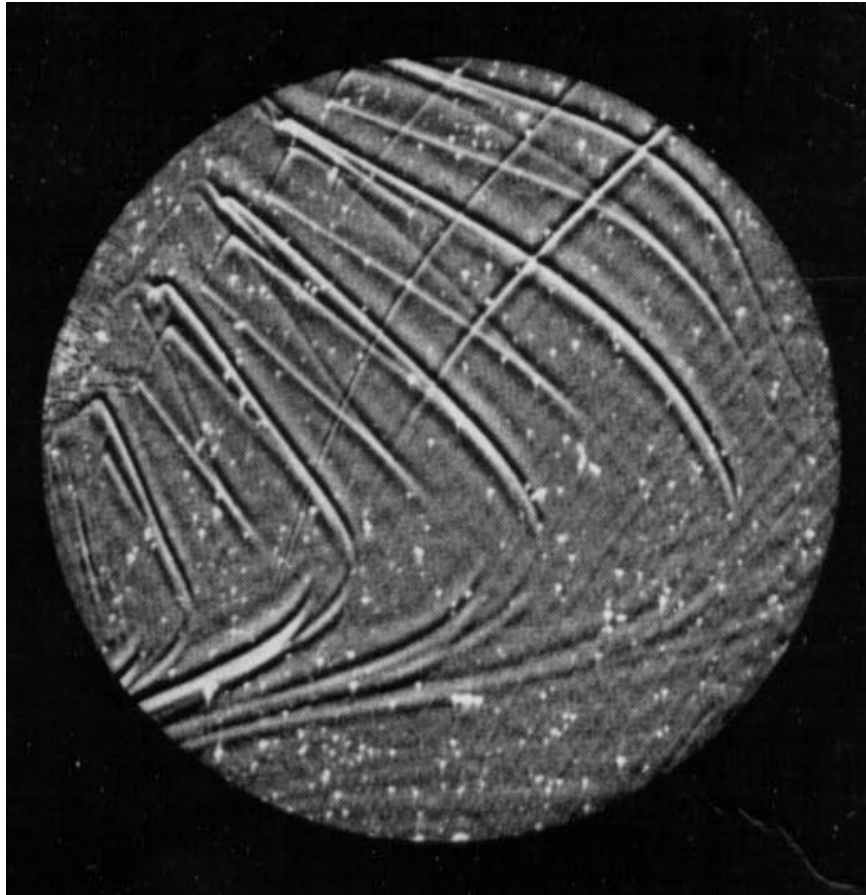


Figure 2. Inhomogeneities in glass – Schlieren method.

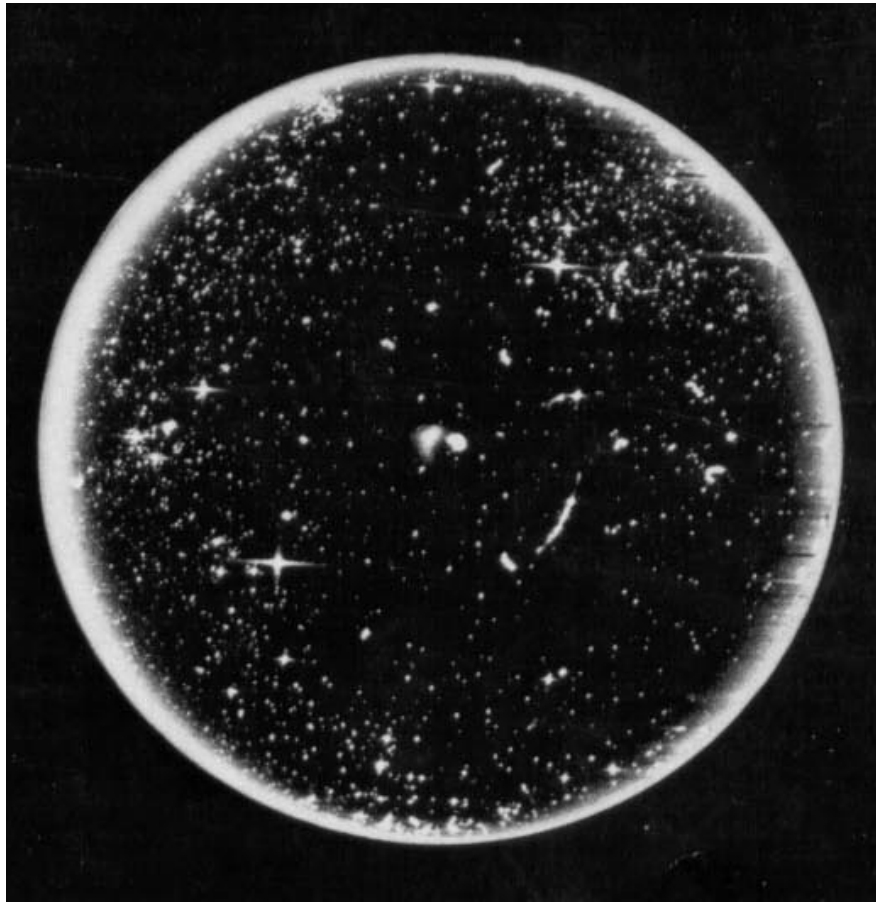


Figure 3. Inhomogeneities in glass – Schlieren method.

6.5 FECO (Fringes of Equal Chromatic Order)

FECO (Fringes of Equal Chromatic Order)

Ref: Born & Wolf, p. 359.

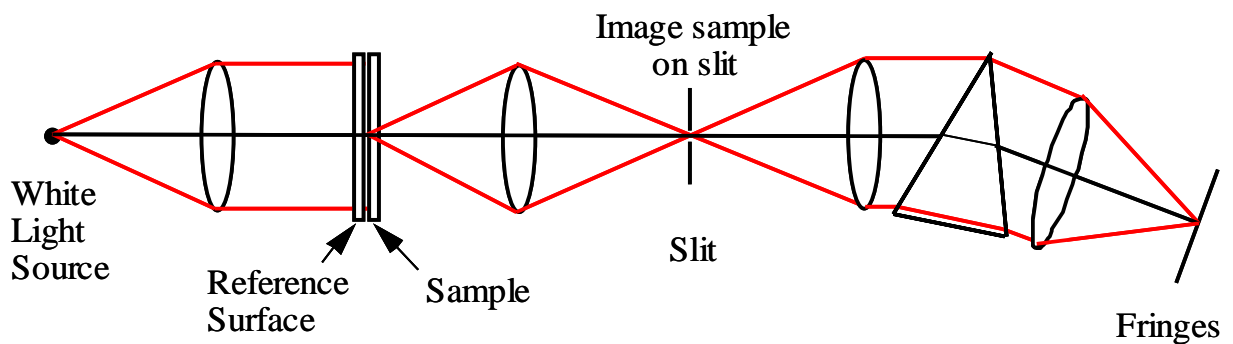
The FECO interferometer is a multiple-beam interferometer in which the test sample is focused onto the entrance slit of a spectrograph. A white light source is used in the interferometer. It can be shown that each fringe gives the profile of the distance between the test surface and the reference surface for the line portion of the surface focused onto the entrance slit.

For multiple-beam interference the transmission is given by

$$I_t = \frac{I_{\max}}{1 + F \sin^2[\delta / 2]} \quad \text{where} \quad \delta = \frac{2\pi}{\lambda_o} 2 n d \cos[\theta] + 2\phi$$

ϕ is the phase change on reflection at each surface.

A schematic diagram of a FECO interferometer is shown below. Both the sample and the reference surface must have high reflectivity so high finesse multiple beam interference fringes are obtained. The sample is imaged onto the entrance slit of a spectrograph



If $n = 1$ and $\theta = 0^\circ$ for a bright fringe of order m

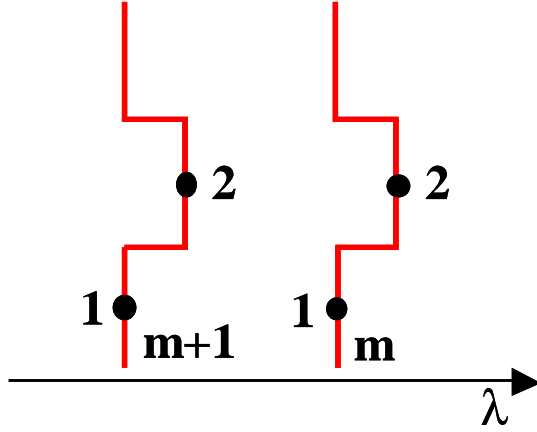
$$\frac{\phi}{\pi} + 2 \frac{d}{\lambda} = m$$

It should be noted that for a given fringe $\frac{d}{\lambda} = \text{constant}$ and

$$\lambda_m = \frac{2d}{m - \frac{\phi}{\pi}}$$

Solving for the height difference across a sample is complicated since $\phi = \phi[\lambda]$. However, with many coatings ϕ can be considered to be independent of λ over the small spectral region used for the analysis. (For more details see Born & Wolf or Jean Bennett, JOSA 54, p. 612 (1964).

The following drawing shows two fringes in the FECO output. The goal is to find the surface height difference between points 1 and 2.



$$d = \left(m - \frac{\phi}{\pi}\right) \frac{\lambda}{2} \quad \text{and} \quad d_2 - d_1 = \left(m - \frac{\phi}{\pi}\right) \left(\frac{\lambda_{2,m} - \lambda_{1,m}}{2}\right)$$

For point 1 and fringe orders m and $m + 1$

$$\left(m - \frac{\phi}{\pi}\right) \lambda_{1,m} = \left(m + 1 - \frac{\phi}{\pi}\right) \lambda_{1,m+1}$$

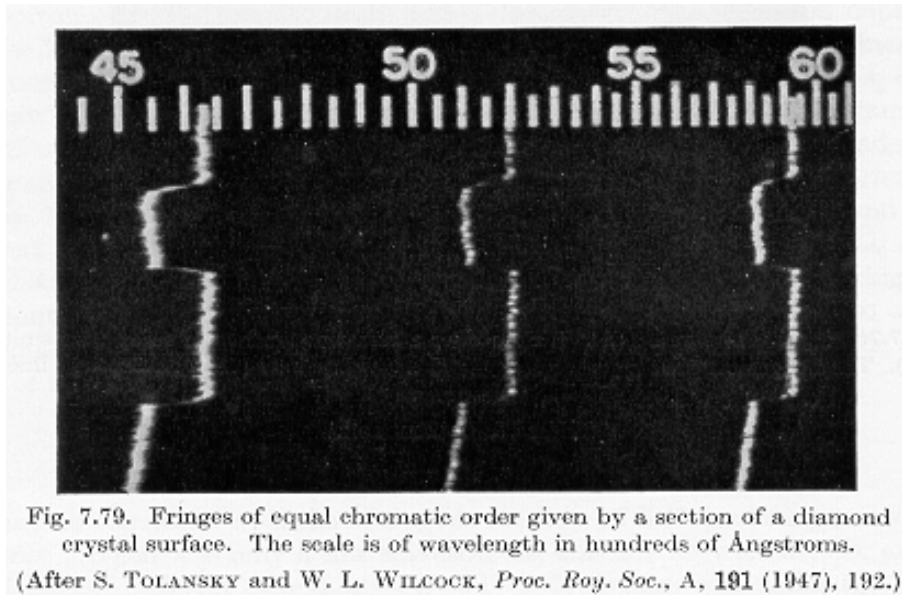
Thus,

$$\left(m - \frac{\phi}{\pi}\right) = \frac{\lambda_{1,m+1}}{\lambda_{1,m} - \lambda_{1,m+1}}$$

and

$$d_2 - d_1 = \frac{\lambda_{1,m+1}}{\lambda_{1,m} - \lambda_{1,m+1}} \left(\frac{\lambda_{2,m} - \lambda_{1,m}}{2}\right)$$

The following figure shows some actual FECO interference fringes (Ref: Born & Wolf).



Since $d_2 - d_1$ is proportional to $\lambda_{2,m} - \lambda_{1,m}$, the profile of the cross-section of an unknown surface is obtained by plotting a single fringe on a scale proportional to the wavelength.

The spectroscopic slit is in effect selecting a narrow section of the interference system and each fringe is a profile of the variation of d in that section since there is exact point-to-point correspondence between the selected region and its image on the slit.

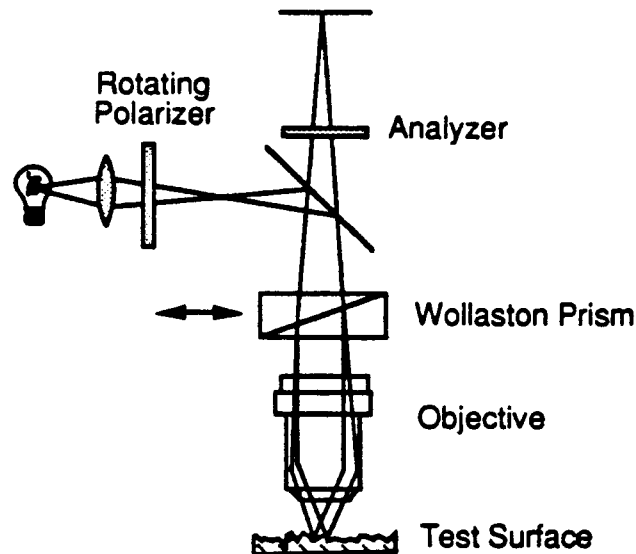
Small changes in d are determined by measuring small changes in λ . There are no ambiguities as to whether a region is a hill or a valley. There are no ambiguities at a discontinuity as we would have with monochromatic light where it is difficult to determine which order belongs to each fringe. Surface height variations in the Angstrom range can be determined.

Two disadvantages are

- 1) we are getting data only along a line and
- 2) the sample being measured must have a high reflectivity.

Nomarski Microscope

The diagram below shows a drawing of the optical layout of a Nomarski microscope. The Nomarski microscope is sometimes called a differential interference contrast (DIC) microscope or a polarization interference contrast microscope.

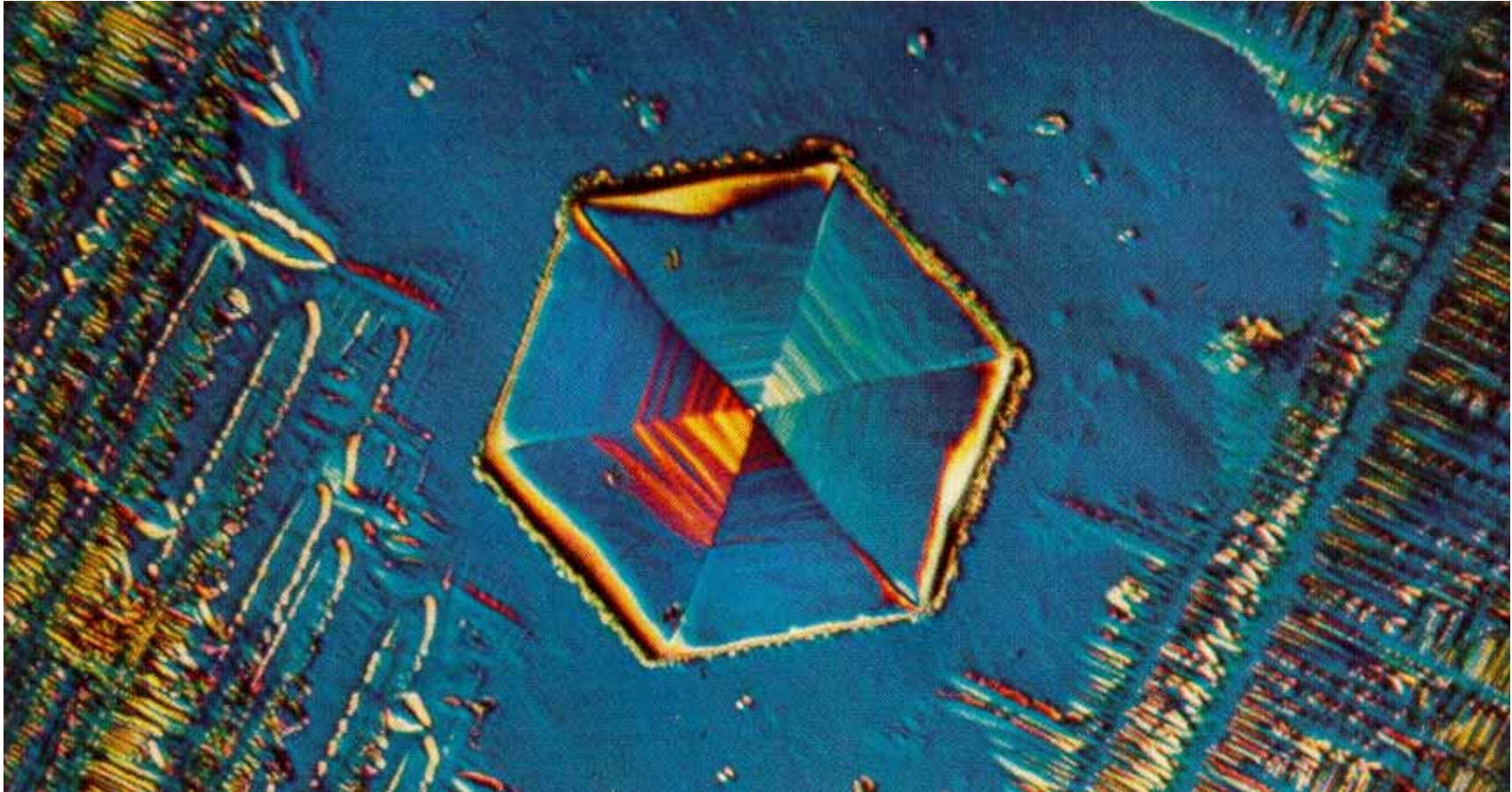


A polarizer after a white light source is used to set the angle of the polarized light incident upon a Wollaston prism. The Wollaston splits the light into two beams having orthogonal polarization, which are sheared with respect to one another. After reflection off the test surface the Wollaston recombines the two beams. A fixed analyzer placed after the Wollaston transmits like components of the two polarizations and generates an interference pattern.

The resulting image shows the difference between two closely spaced points on the test surface. The point separation (shear at the test surface) is usually comparable to the optical resolution of the microscope objective and hence only one image is seen. The image shows slope changes and it appears as though the surface has been illuminated from one side. Like a shearing interferometer, only detail in the direction perpendicular to the shear is seen. In other words, if the shear is in the x direction, only features parallel to the y-axis will be seen. Detail parallel to the x direction will not be visible without rotating the test surface or the Wollaston prism.

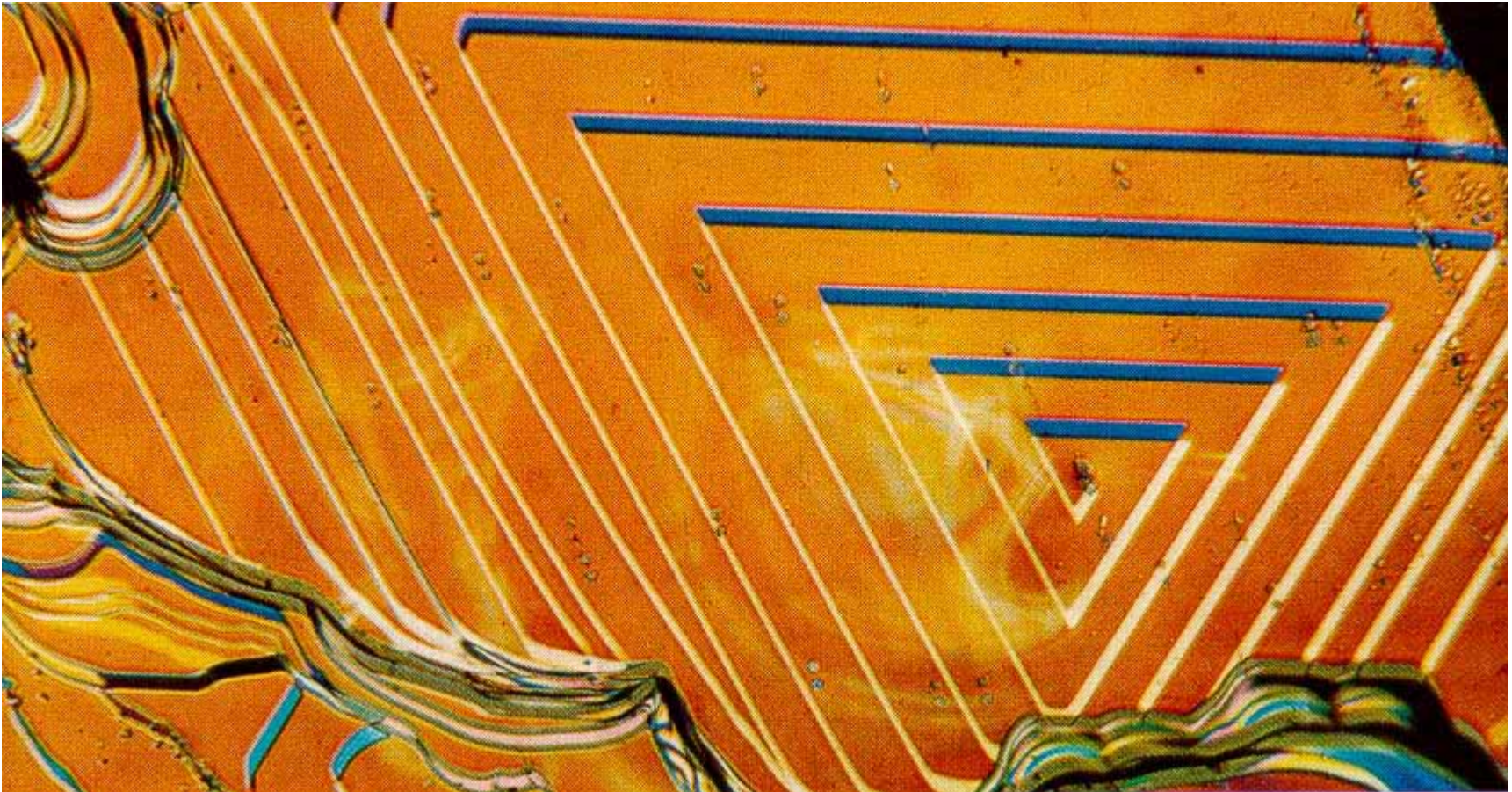
The path difference between the two beams can be adjusted by laterally translating the Wollaston prism. When the axes of the polarizer and analyzer are parallel and the prism is centered, the path lengths are equal and white light is seen for a perfect test surface with no tilt. When the polarizer and analyzer are crossed and the prism centered, no light gets through. When the prism is translated sideways, the two beams have unequal paths and different colors are seen. The color for a specific feature on the test surface depends upon the path difference between the two beams for that point. The color changes indicate the surface slopes. When the polarizer before the prism is rotated, the relative intensities of the two orthogonal polarized beams change, and the colors change.

Crystals of ammonium alum seen with differential polarization microscope



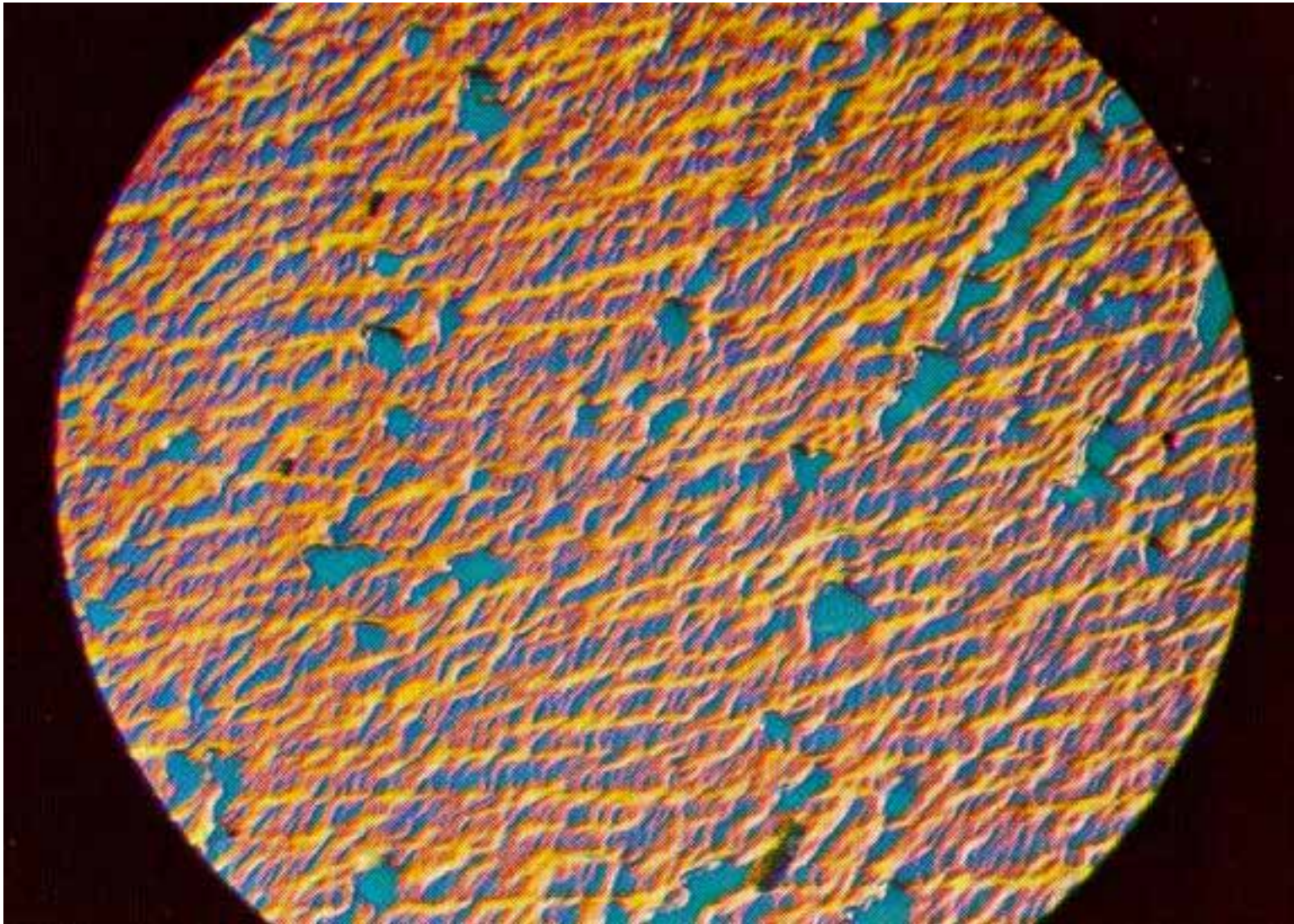
Ref: "Atlas of Optical Phenomena", Vol. 2, Francon et al.

Crystals of silicon carbide seen with differential polarization microscope

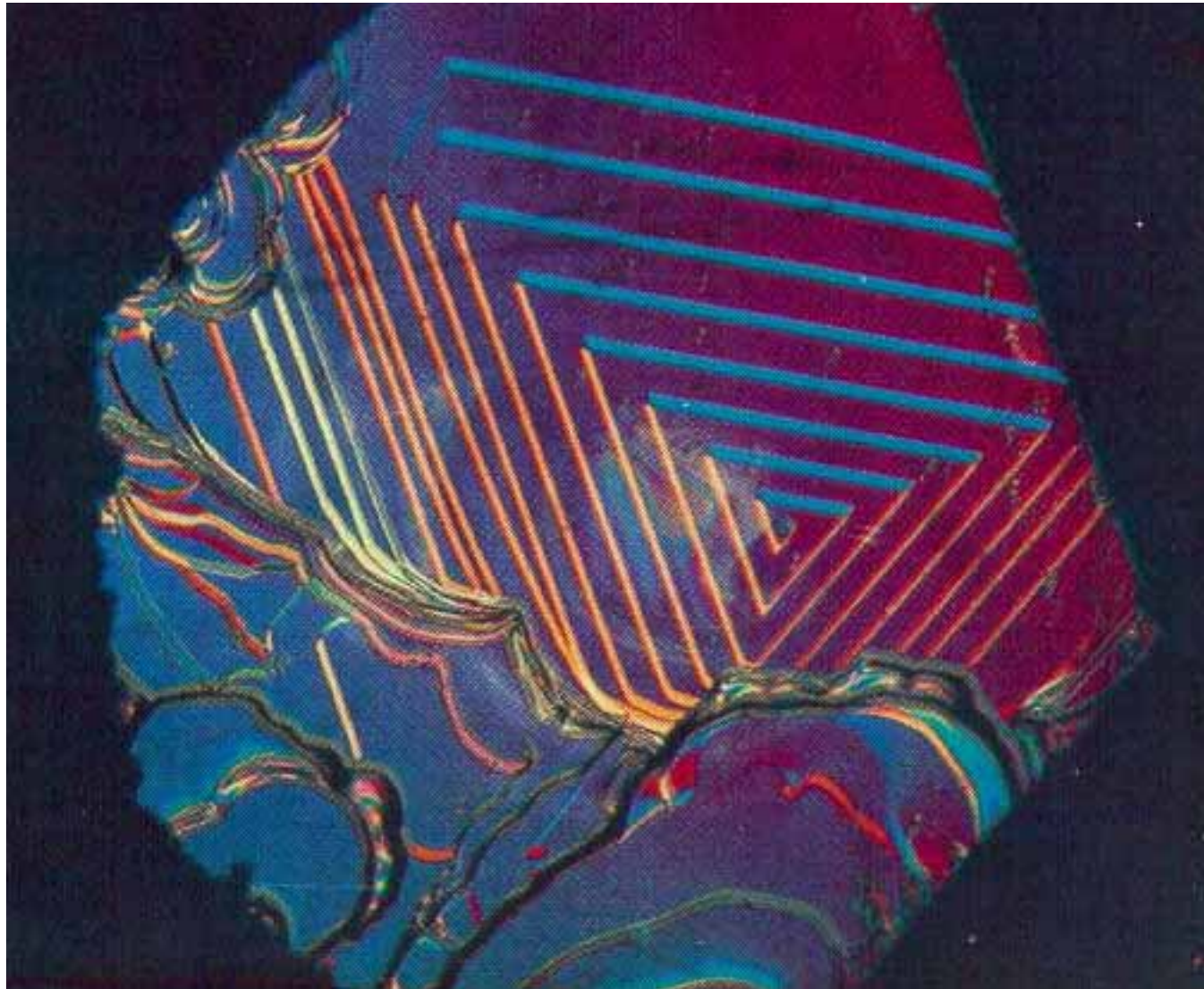


Ref: "Atlas of Optical Phenomena", Vol. 2, Francon et al.

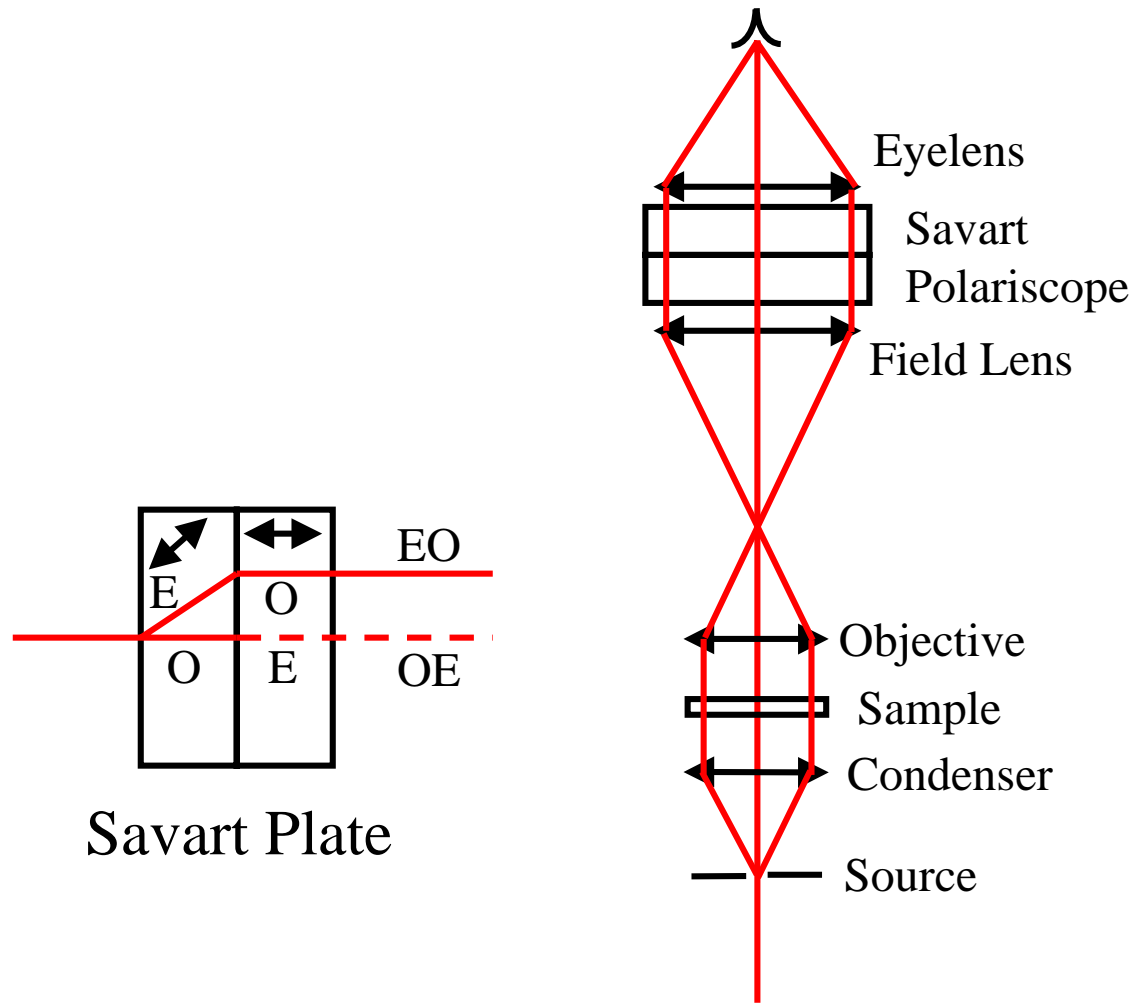
Defects of germanium plate seen with differential polarization microscope



Silicon carbide crystal seen with differential polarization microscope



Francon Interference Eyepiece



Non-Contact Optical Profilers for Measurement of Surface Microstructure

•Advantages

Non-contact measurement
2D or 3D surface topography
Visual qualitative surface inspection
Vertical resolution suitable for super-polished optics
Fast measurement and analysis

•Disadvantages

Measures phase change as well as profile
Lateral resolution limited by optical resolution

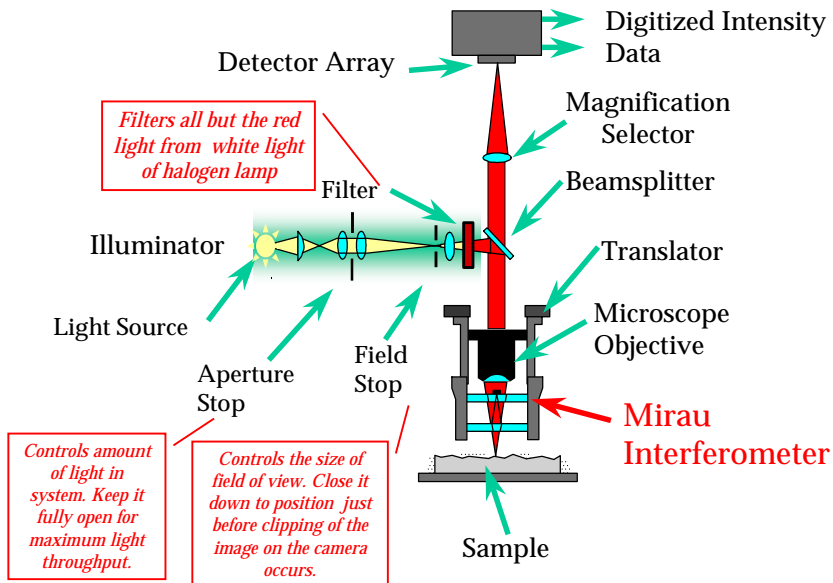
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Advantages of White Light over Laser Light

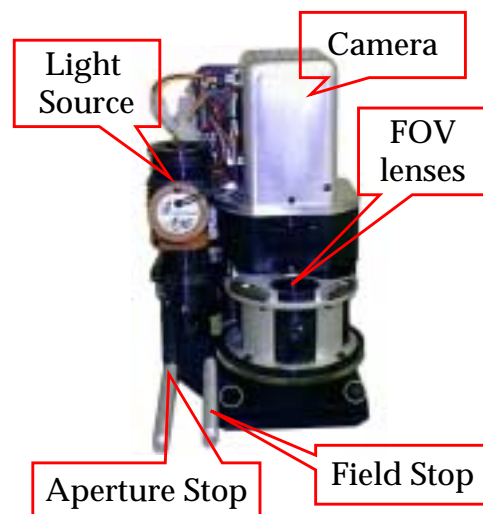
- **Lower noise**
No spurious fringes
- **Multiple wavelength operation**
Measure large steps
- **Focus easy to determine**

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Interference Microscope Diagram

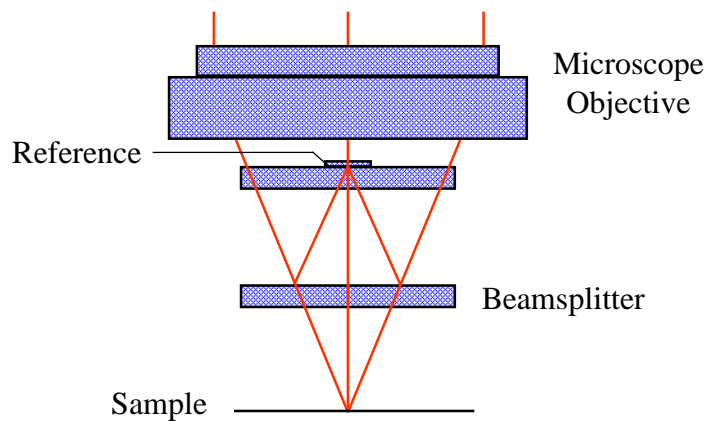


Typical Instrument



Mirau Interferometer

(10X, 20X, 50X)

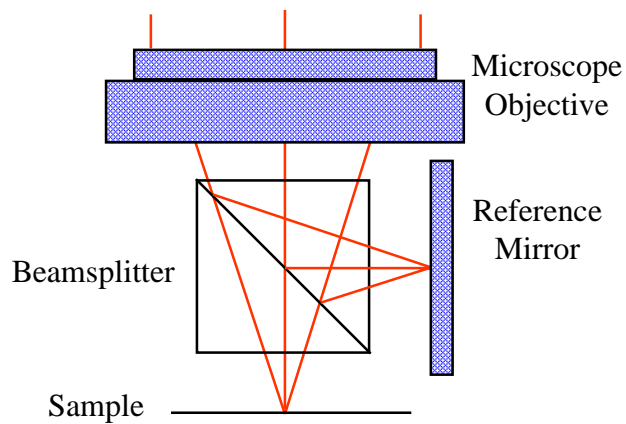


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Michelson Interferometer

(1.5X, 2.5X, 5X)

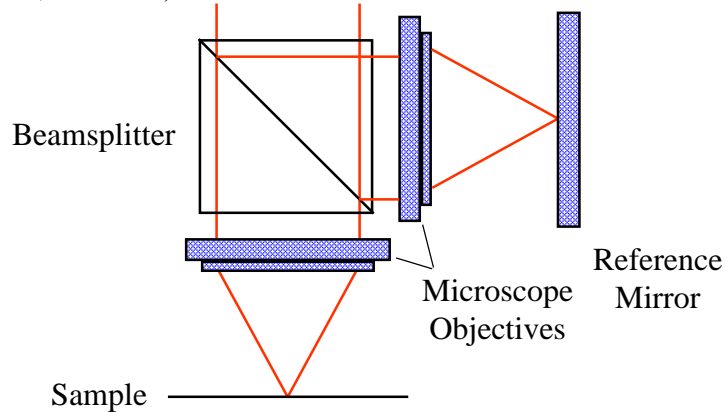


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Linnik Interferometer

(100 X, NA 0.95)



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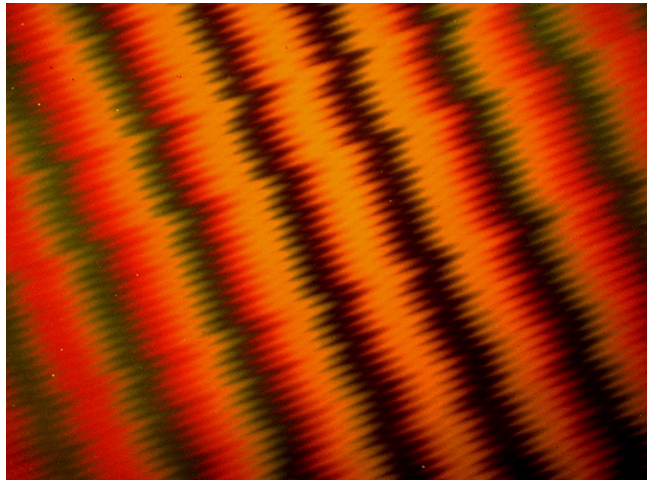
Interference Objectives

- **Mirau**
 - Medium magnification
 - Central obscuration
 - Limited numerical aperture
- **Michelson**
 - Low magnification, large field-of-view
 - Beamsplitter limits working distance
 - No central obscuration
- **Linnik**
 - Large numerical aperture, large magnification
 - Beamsplitter does not limit working distance
 - Expensive, matched objectives

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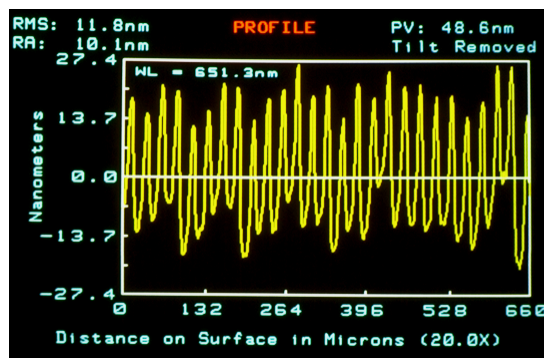
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White Light Interferogram



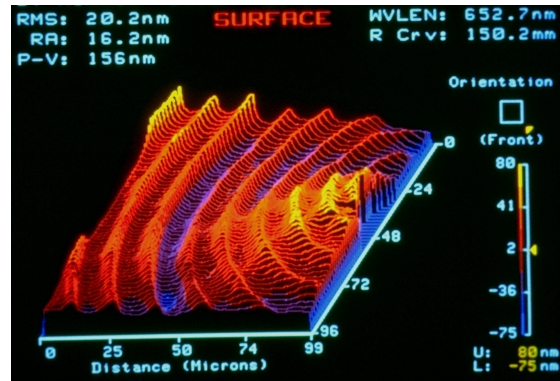
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Profile of Diamond Turned Mirror

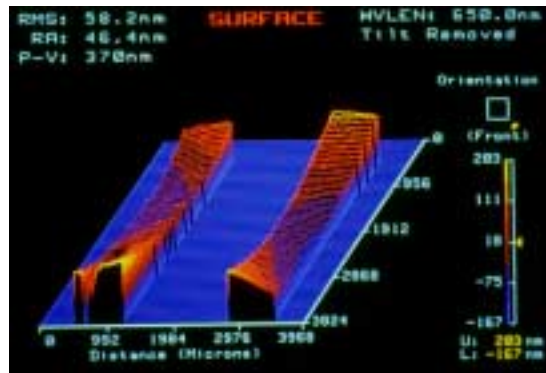


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Diamond Turned Mirror



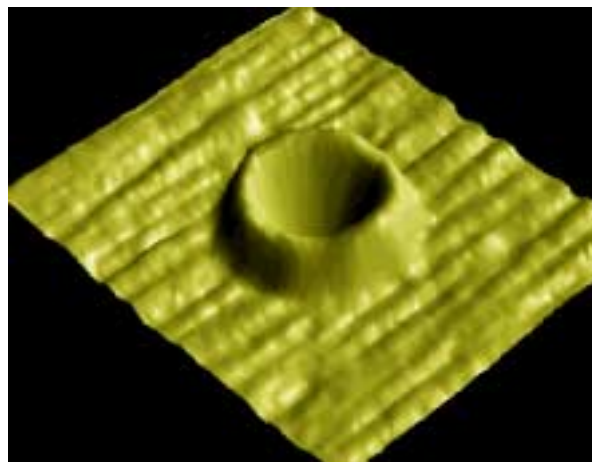
Magnetic Recording Head



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Typical Measurements Laser Textured Magnetic Hard Disk



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