instruments

Solar Physics course lecture 3

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Frans Snik
BBL 415 (710)
f.snik@astro.uu.nl
www.astro.uu.nl/~snik

info from photons

- spatial (x,y)
- temporal (t)
- spectral (λ)
- polarization ($\vec{S}$)

$\rightarrow$ usually photon starved at the diffraction limit!

instruments

info from photons

- filter imaging
- spectroscopy
- (spectro-)polarimetry

X-ray, UV, visible, IR, radio?

resolution?

time coverage?

disk coverage?

imaging optics

Terminology

- reimaging image and pupil planes
- diffraction limited optics:

    no aberrations > Airy disk across field
- F/#=N=f_{eff}/D : “beam speed”
- telecentric: pupil in infinity

    → same transmission across the field

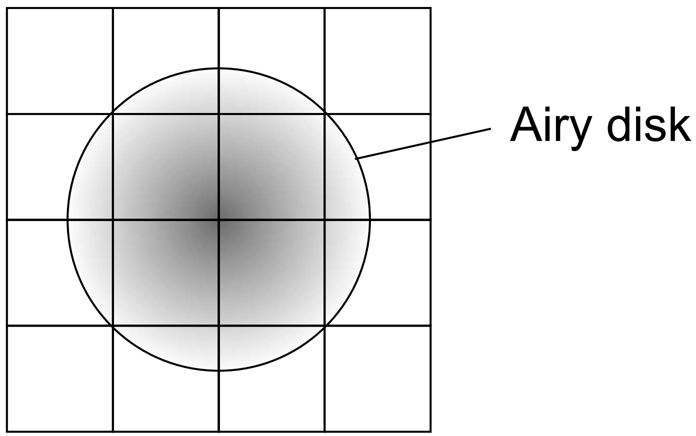
    → field independent of defocus

instruments

detectors

- (photographic)
- CCD/CMOS
- IR array

pixel size (~10x10 μ)
Nyquist sampling



- read noise
- dark current
- read-out spead

instruments

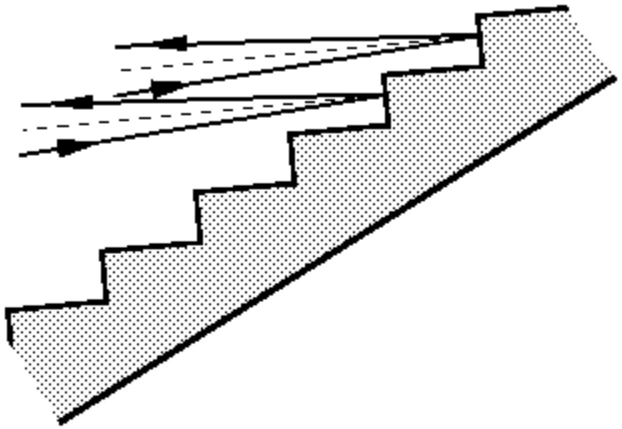
spectrographs (3.3)

- (prism)
- Czerny-Turner (Ebert-Fastie)
- Littrow
- (Fourier Transform Spectrometer)

grating (3.3.1)

$$m\lambda = a(\sin\alpha + \sin\beta) \qquad (3.27)$$

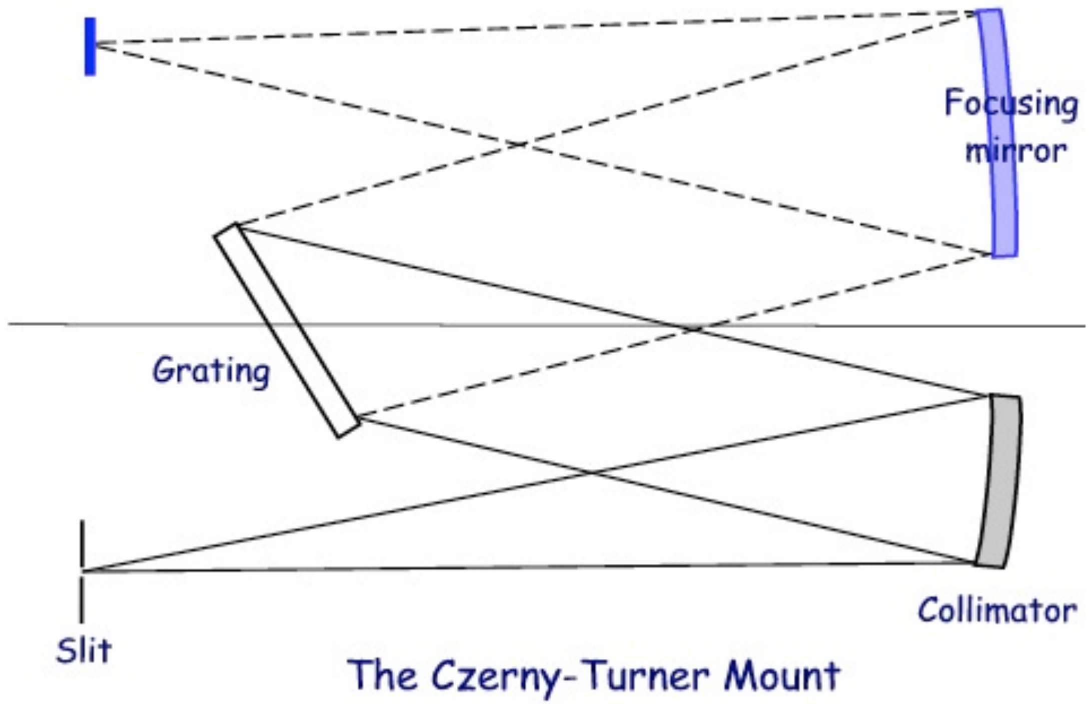
$$\frac{d\beta}{d\lambda} = \frac{m}{a\cos\beta} \qquad (3.28)$$



blazed echelle grating
→high resolution at high order
→most energy into blaze angle
→multiple-order spectrum using cross-disperser prism

Czerny-Turner

- (curved) slit
- coma cancelled by symmetric design
- astigmatism present



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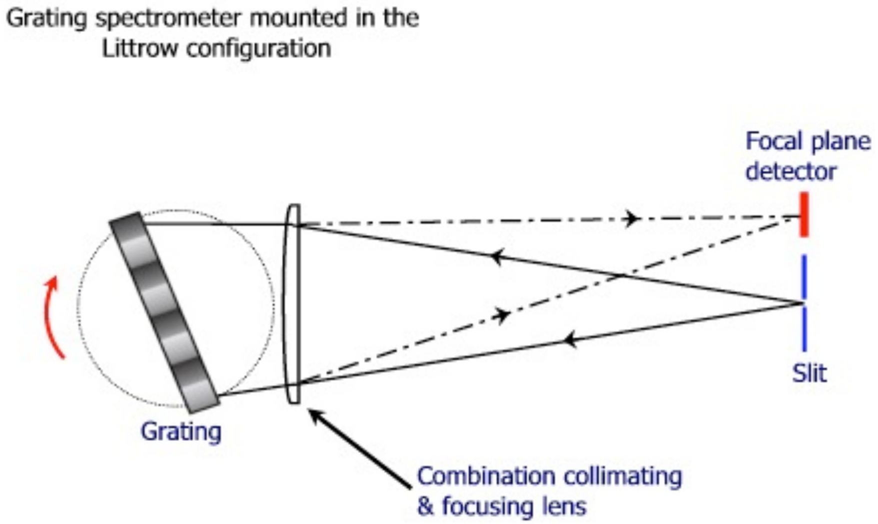
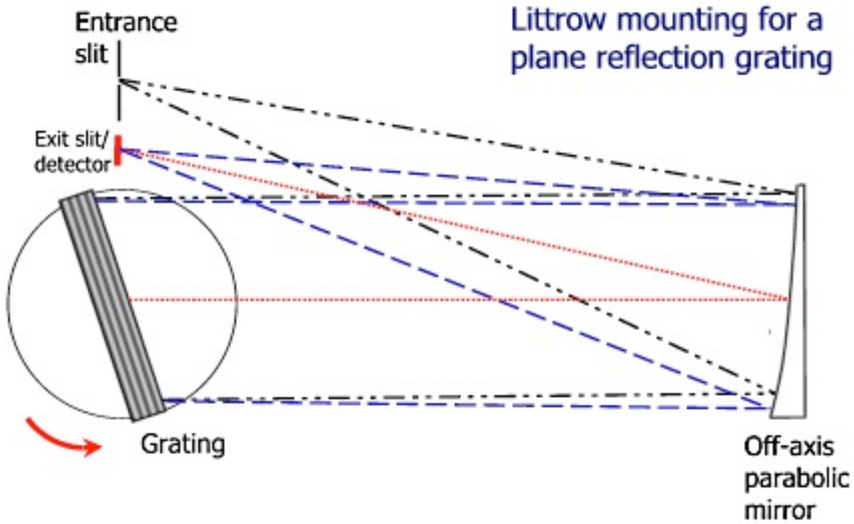
Littrow

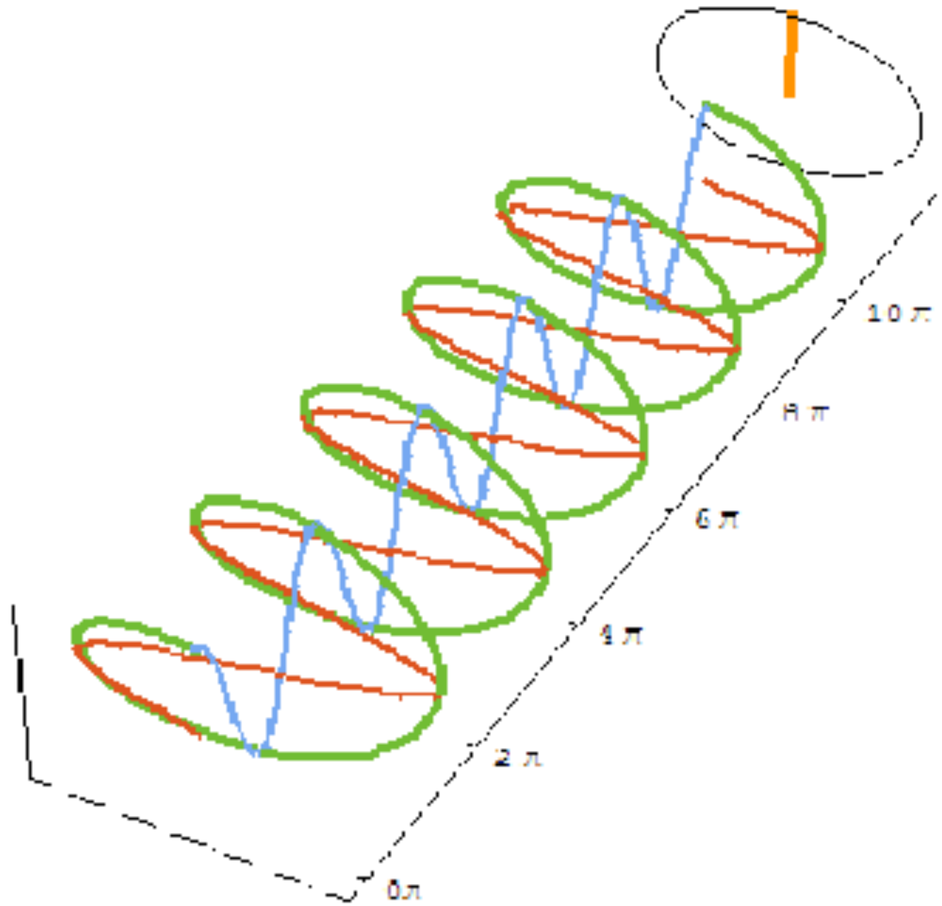




- more compact design

instruments

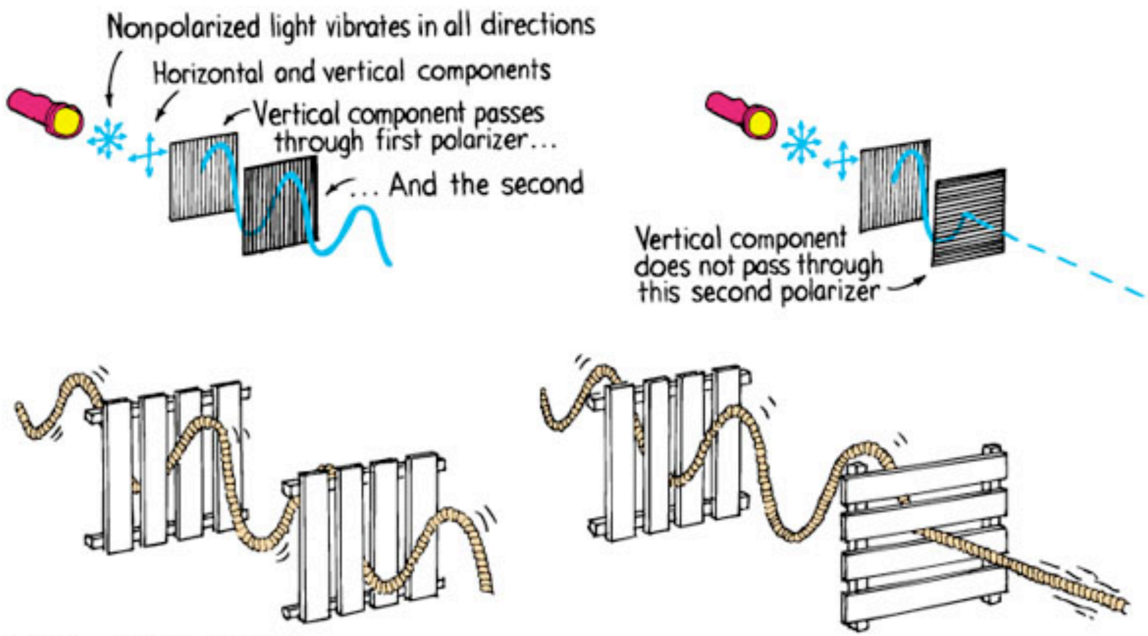
polarization optics



polarization optics

polarizers

- wire grid



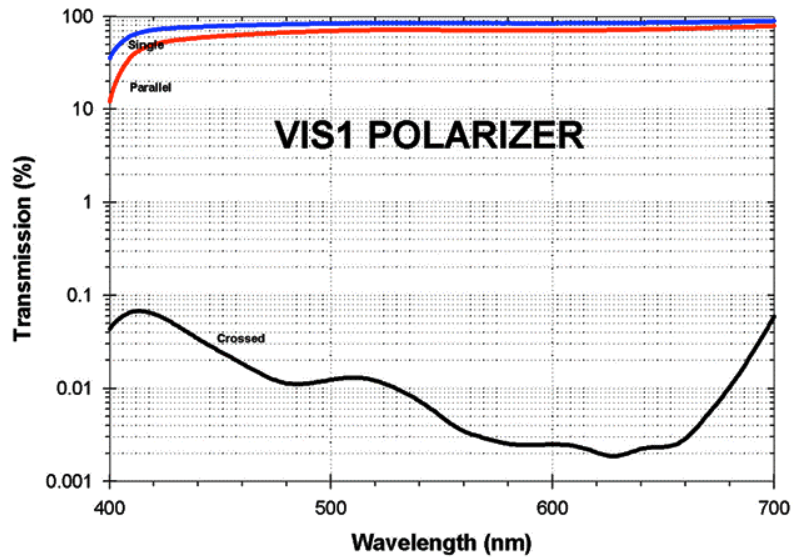
?!?!

instruments

polarization optics

polarizers

- stretched polymer (dichroism)

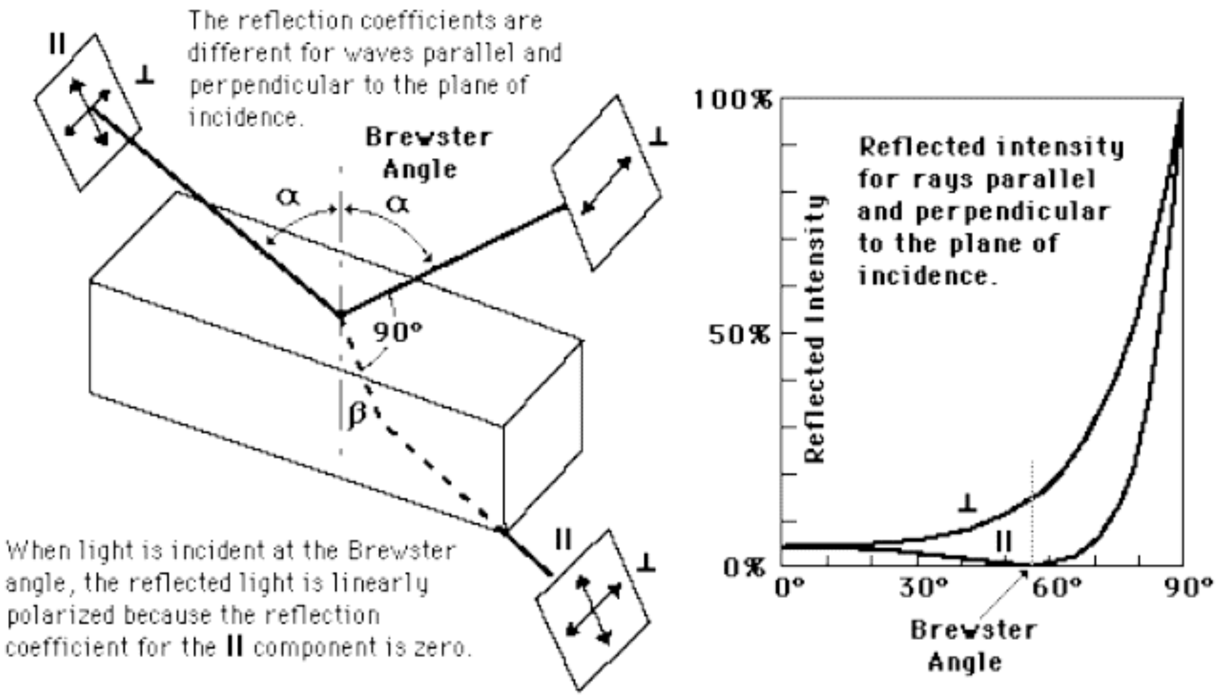


instruments

polarization optics

polarizers

- Brewster angle

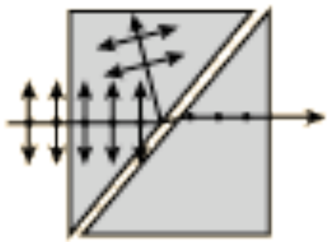


polarization optics

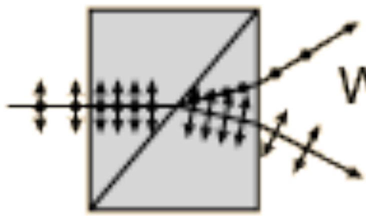
polarizers

- birefringent crystal

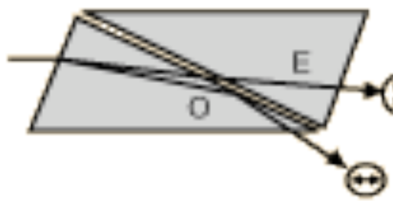
  n_o & n_e



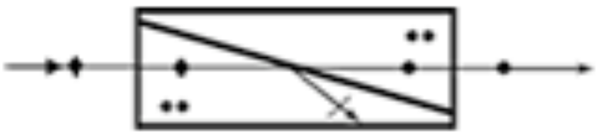
Glan-Foucault Polarizer



Wollaston Prism



Nicol Prism



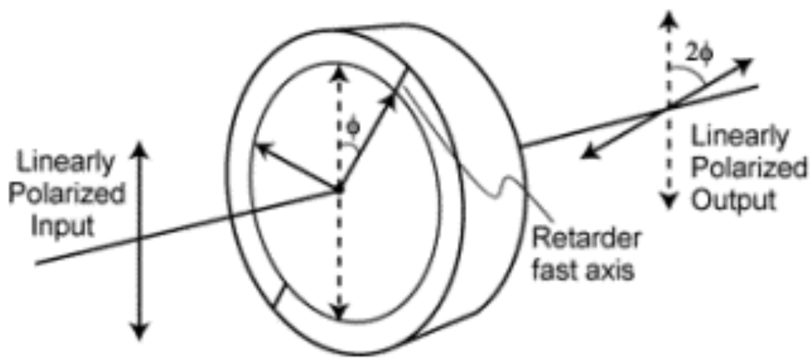
Glan-Thompson Prism

instruments

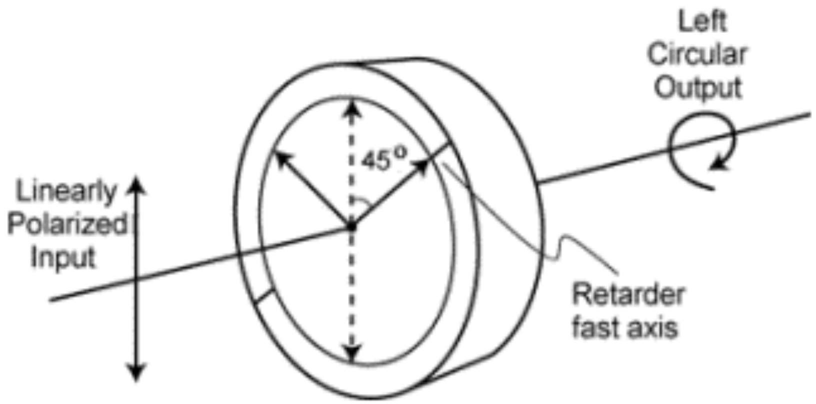
polarization optics

retarders

→introduction of phase difference



half wave plate



quarter wave plate

$$\delta = \frac{2\pi e(n_o - n_e)}{\lambda}$$

chromatic and temperature sensitive for birefringent plates

instruments

polarization optics

retarders

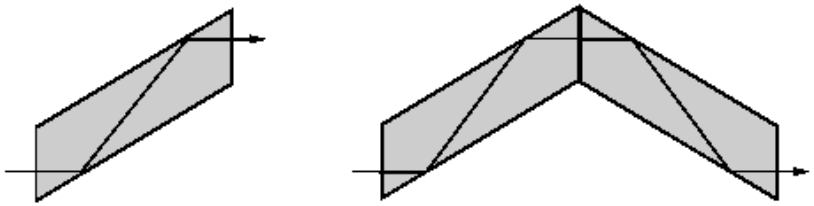
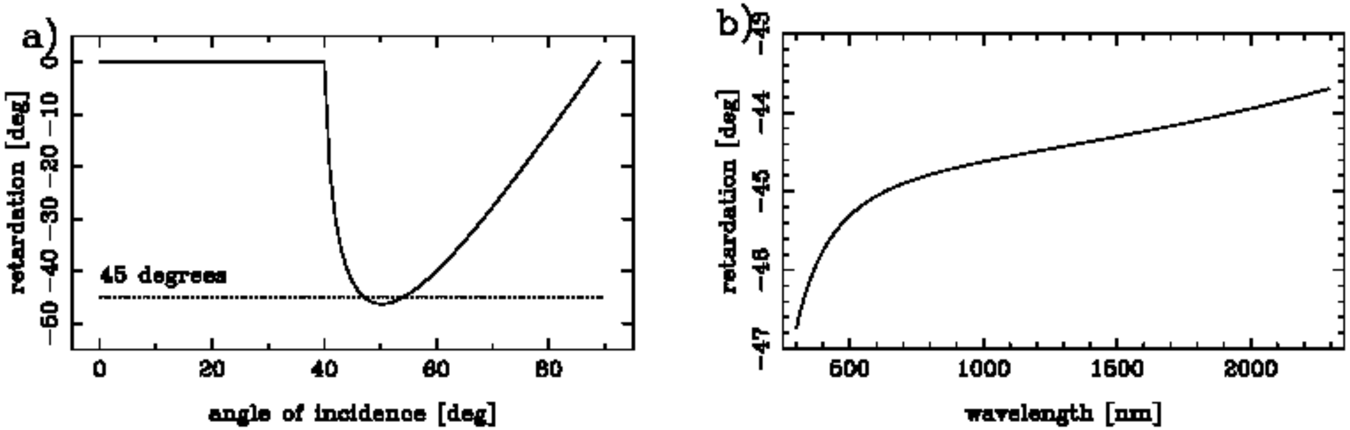


FIGURE 8. Traditional arrangements for quarter-wave (left) and half-wave (right) Fresnel rhombs.

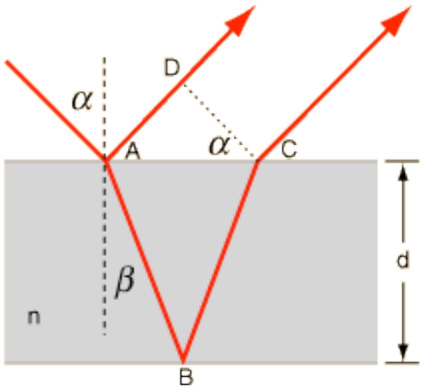


filters

- interference filter
- Fabry-Pérot interferometer
- Lyot filter
- (Michelson interferometer)

instruments

interference filter



Optical pathlength difference Γ :

$$\Gamma = n(AB + BC) + AD$$

$$AB = \frac{d}{\cos\beta} \qquad AD = (2d\tan\beta)\sin\alpha$$

$$AD = 2d\tan\beta(n\sin\beta)$$

Collecting terms:

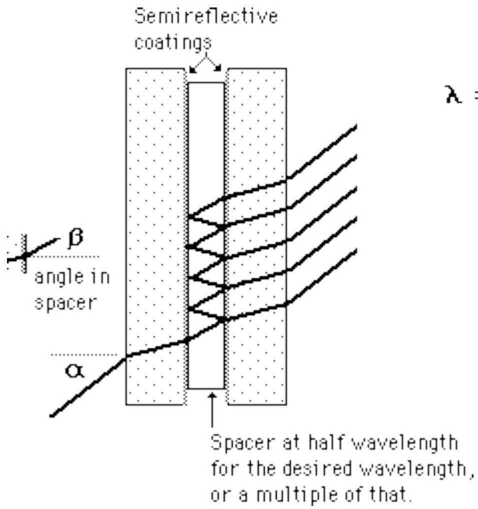
$$\Gamma = 2nd\left[\frac{1}{\cos\beta} - \tan\beta\sin\beta\right]$$

$$\Gamma = 2nd\left[\frac{1-\sin^2\beta}{\cos\beta}\right] = 2nd\cos\beta$$

Destructive → $2nd\cos\beta = m\lambda$ ← Constructive

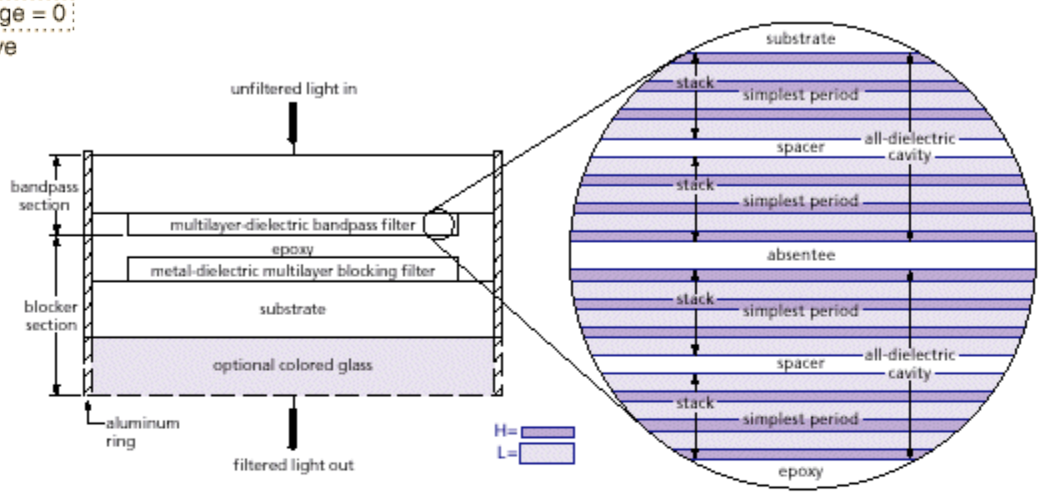
Phase change = π | Phase change = 0

Constructive → $2nd\cos\beta = (m - \frac{1}{2})\lambda$ ← Destructive

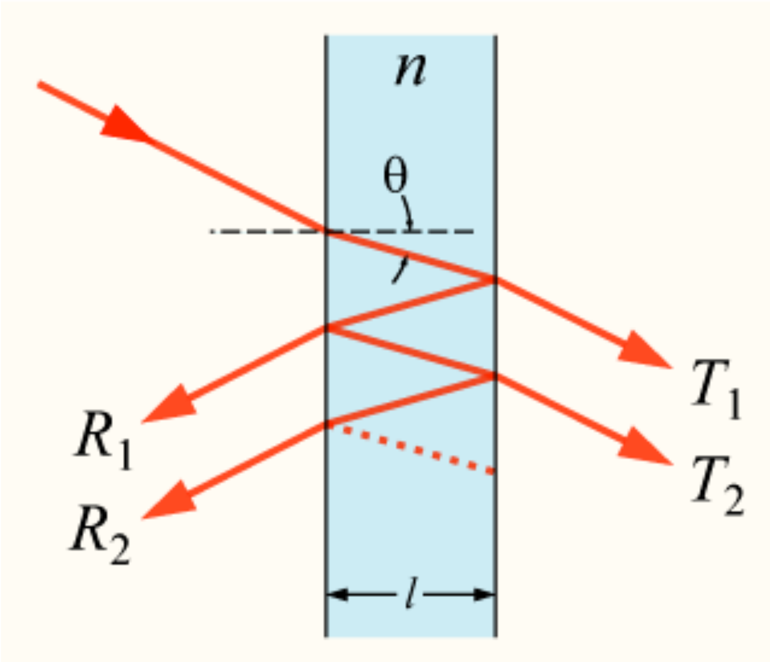


$$\lambda = \lambda_0\sqrt{1 - \frac{\sin^2\alpha}{n^2}}$$

~10 Å bandpass



Fabry-Pérot interferometer (3.4.4)



$$A = T\left(1 + \sum_n R^n e^{ni\delta}\right) = \frac{T}{1 - \mathrm{Re}^{i\delta}} \qquad (3.49)$$

Fabry-Pérot interferometer

$$I = I_{max} \frac{T^2}{(1-R)^2 + 4R\sin^2(\delta/2)}$$ (3.51)

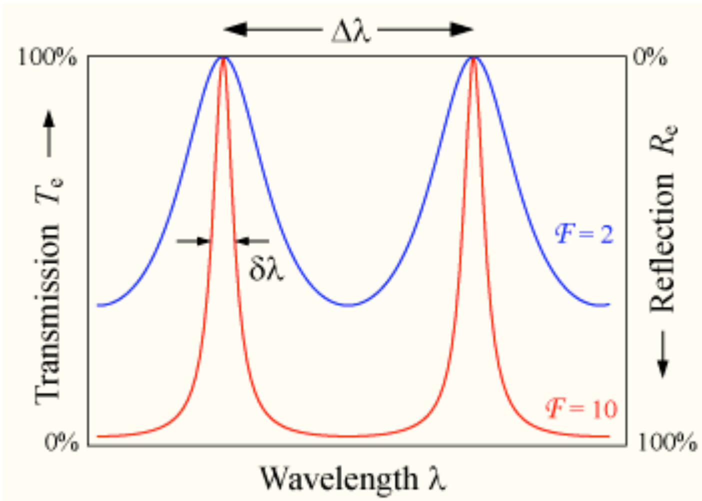
$FSR = \lambda^2 / 2nd\cos\theta$ = free spectral range (peak separation)

$\delta\lambda = FSR / F$

$F = \frac{\pi\sqrt{R}}{1-R}$ = finesse

(3.52-53)

R→1



Fabry-Pérot interferometer

- collimated beam
  - spectral purity
  - spectral dependency on angle
  - image degradation in pupil plane
- telecentric beam
  - pupil apodization
  - defocus
  - field independence
  - high image quality

Lyot filter (3.4.1-2)

birefringent stages
sandwiched
between polarizers

$$I = A^2 \cos^2(\delta/2)$$

(3.37)

- FSR from thinnest stage
- bandpass from thickest stage

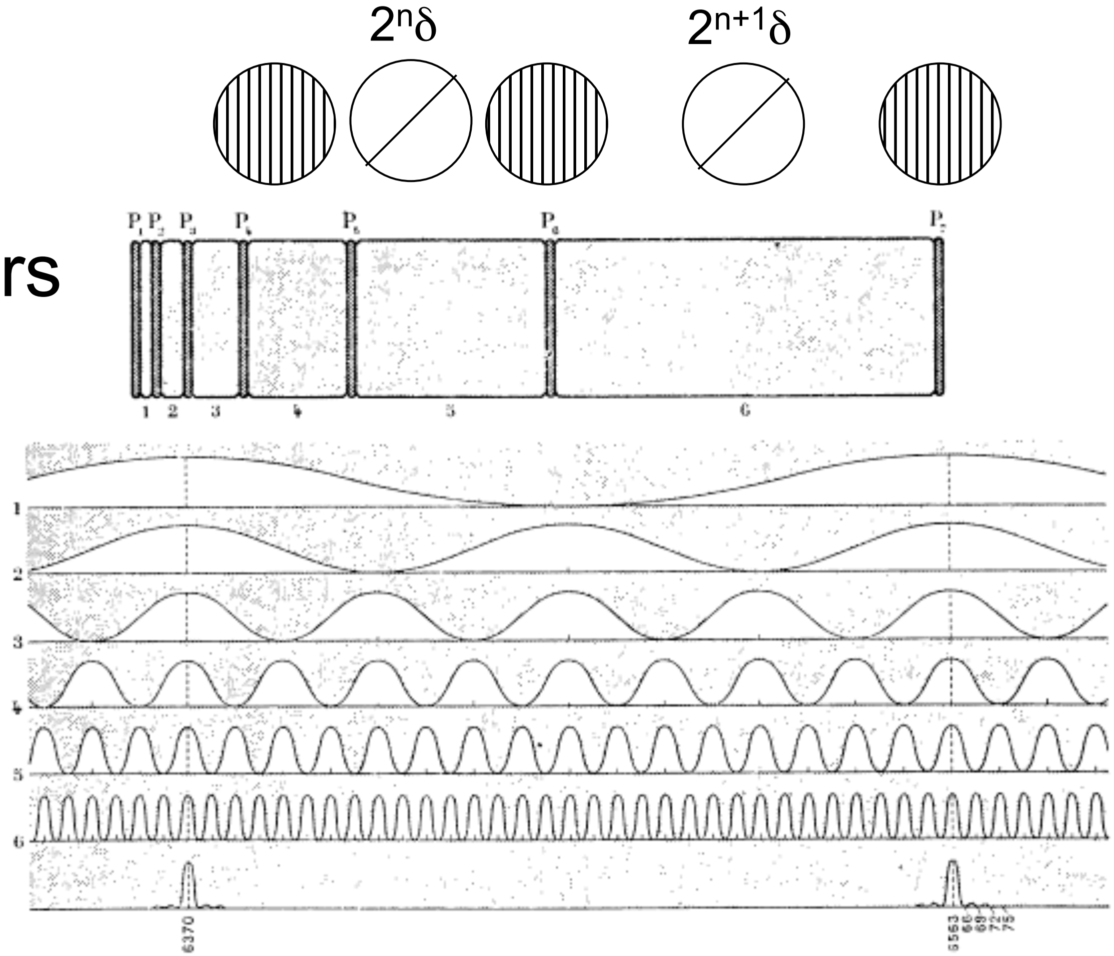


FIG. 1. — Schéma et principe du filtre monochromatique polarisant.

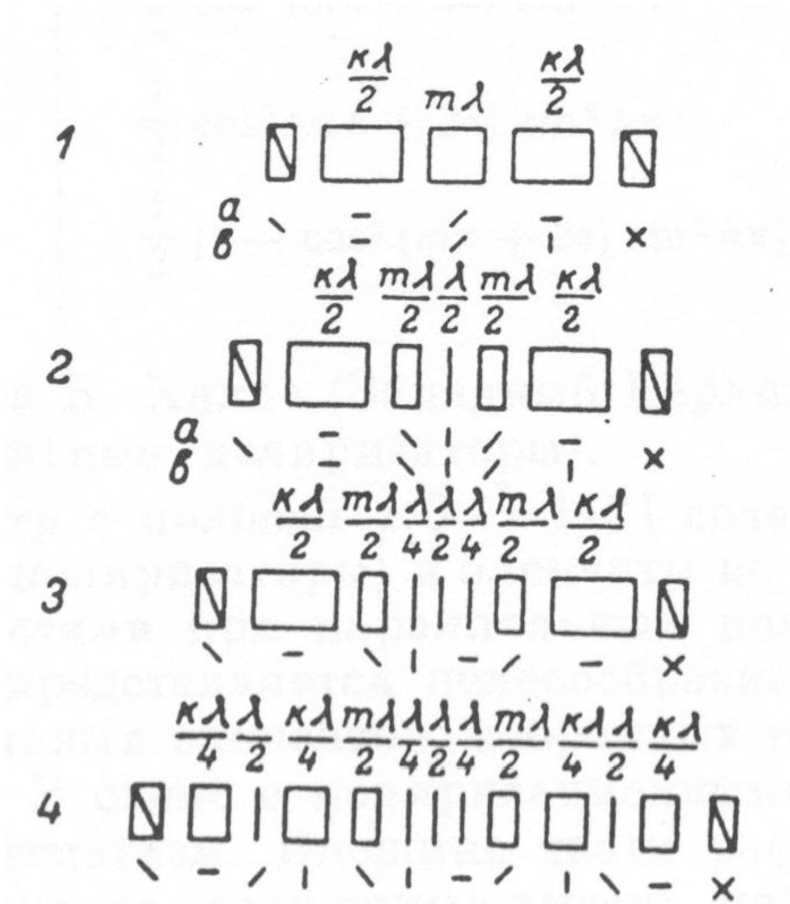
Lyot filter

- rotating waveplates introduce addional phase shift

  → wavelength tuning
- Evans split

  → wide field

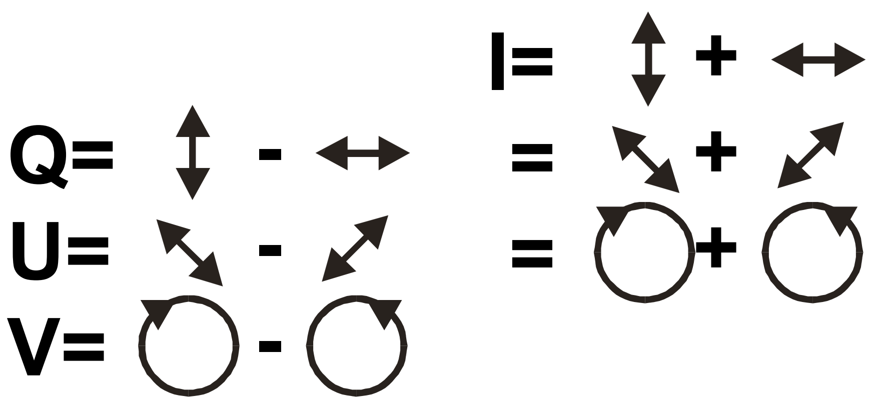
  → extra stages with same number of polarizers

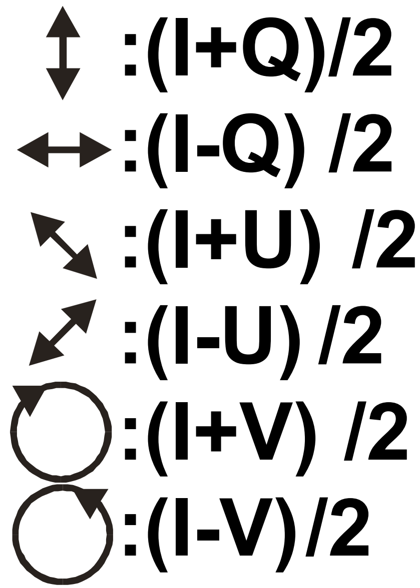


Stokes vector

operational and full description of polarization

$$\vec{S} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$





→differential photometry

Q/I, U/I, **V/I** = polarization degree

beware of sign conventions!

Mueller matrices

$$\vec{S}_{out} = M_n \cdot M_{n-1} \cdot \ldots \cdot M_2 \cdot M_1 \cdot \vec{S}_{in}$$

$$M_{rot} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha & \sin 2\alpha & 0 \\ 0 & -\sin 2\alpha & \cos 2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$M_{pol} = \frac{1}{2}\begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$M_{coord,mir} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$M_{ret} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\delta & -\sin\delta \\ 0 & 0 & \sin\delta & \cos\delta \end{pmatrix}$$

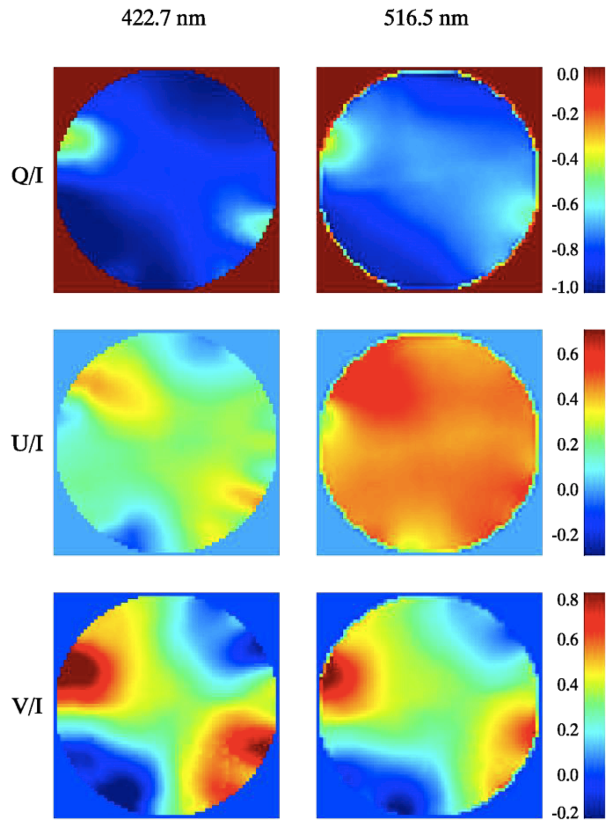
Mueller matrices

- Any non-normal reflection/refraction creates or modifies polarization.
- 45° Al mirror:

$$M_{mir} = \begin{pmatrix} 1.000 & 0.028 & 0 & 0 \\ 0.028 & 1.000 & 0 & 0 \\ 0 & 0 & -0.983 & -0.180 \\ 0 & 0 & 0.180 & -0.983 \end{pmatrix}$$

Mueller matrices

- Stresses in glass elements produce birefringence.



courtesy: Alex Feller

instruments

polarimetry

=measurement of Stokes vector.

I,V: magnetogram

I,Q,U,V: vector magnetogram

→other lectures

modulation & demodulation

need multiple measurements to determine (components of) the Stokes vector

- temporal modulation

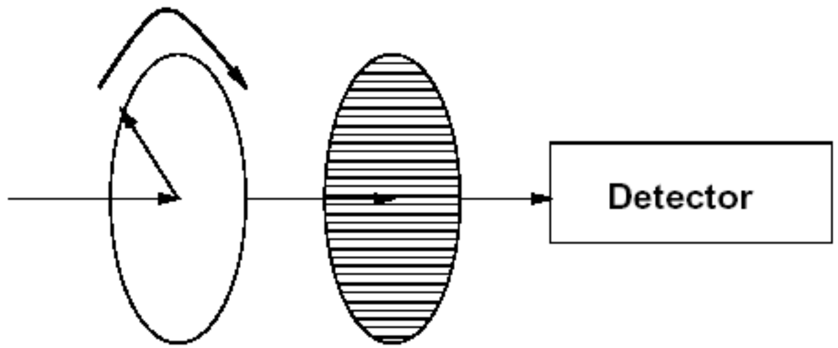
→ susceptible to seeing

- spatial modulation

→ 2 different detectors (parts)

modulation & demodulation

- rotating waveplate + ‘selection’ polarizer

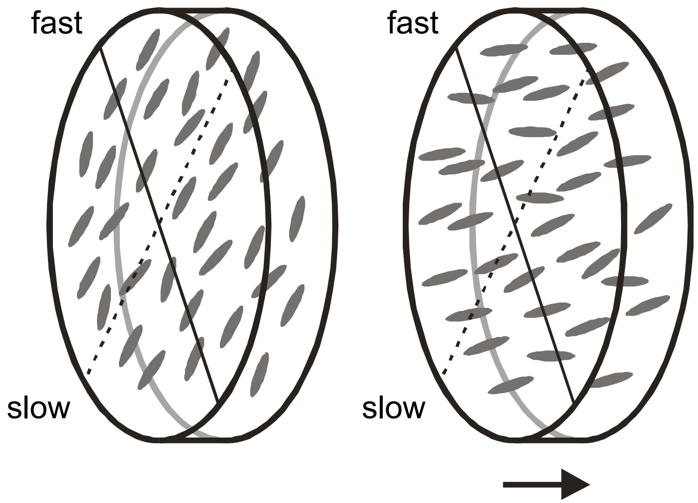


→linear combinations of I with Q, U and V

used in Hinode-SOT

modulation & demodulation

Liquid Crystal Variable Retarders (LCVRs)

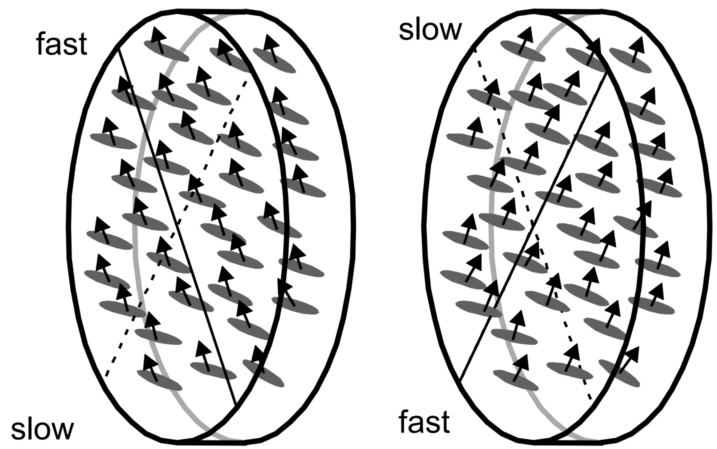


V=0 $\delta = \delta_{max}$

V $\delta < \delta_{max}$

~20 ms

ferroelectric Liquid Crystals (fLCs)



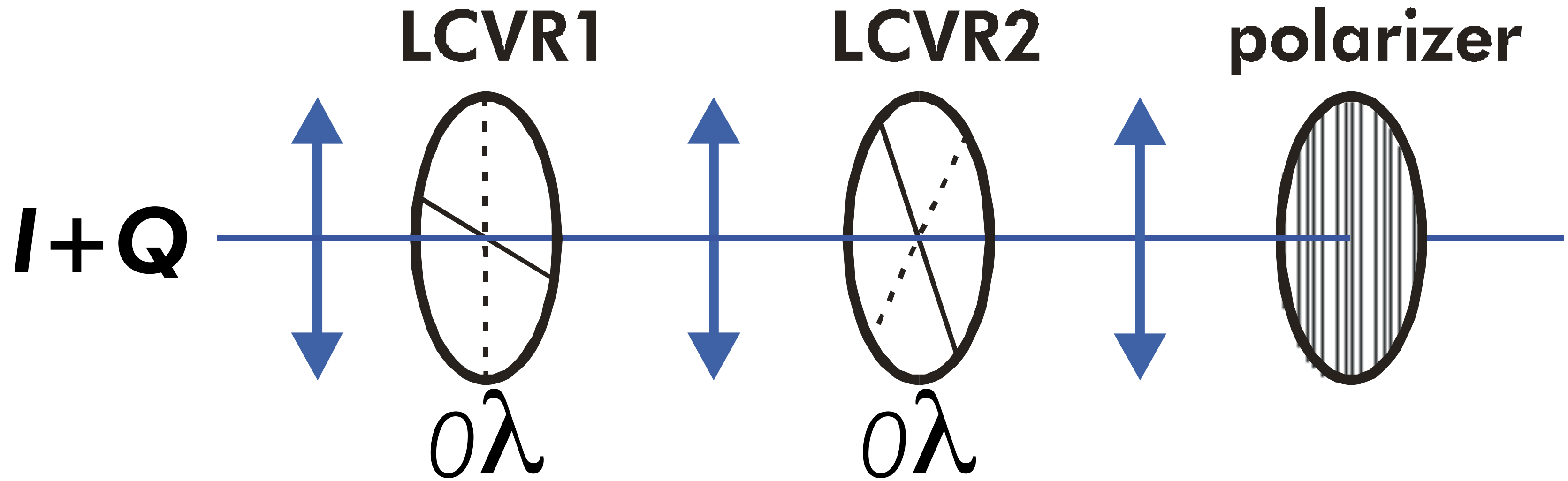
V<0

V>0

~100 μs

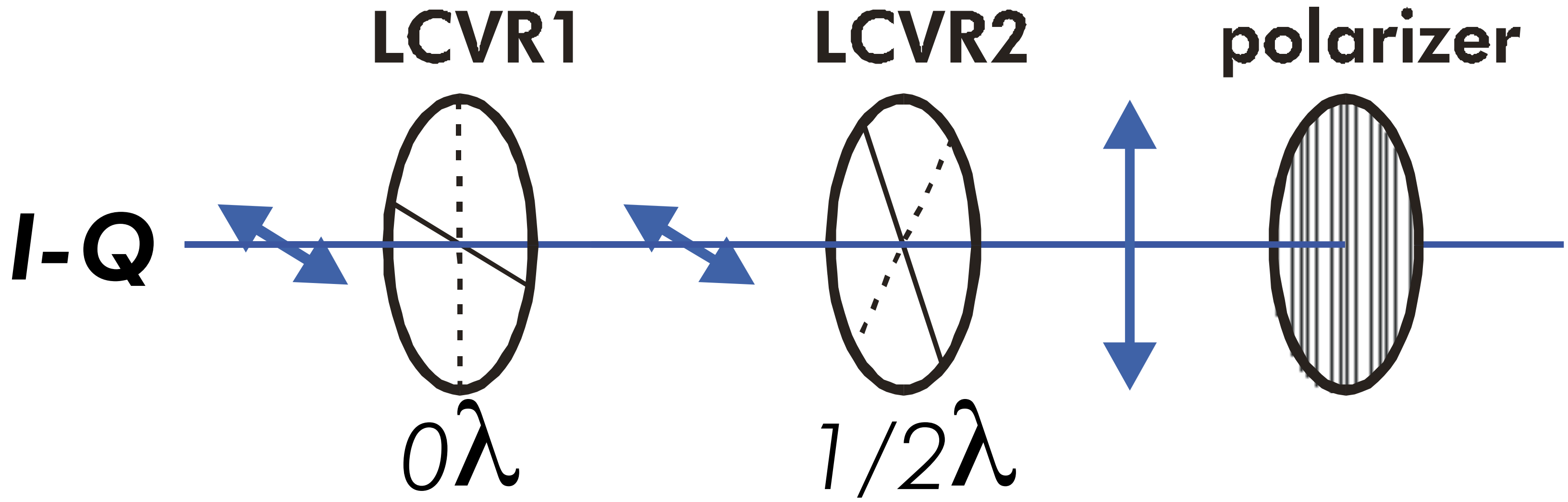
modulation & demodulation

- 2 LCVRs + polarizer



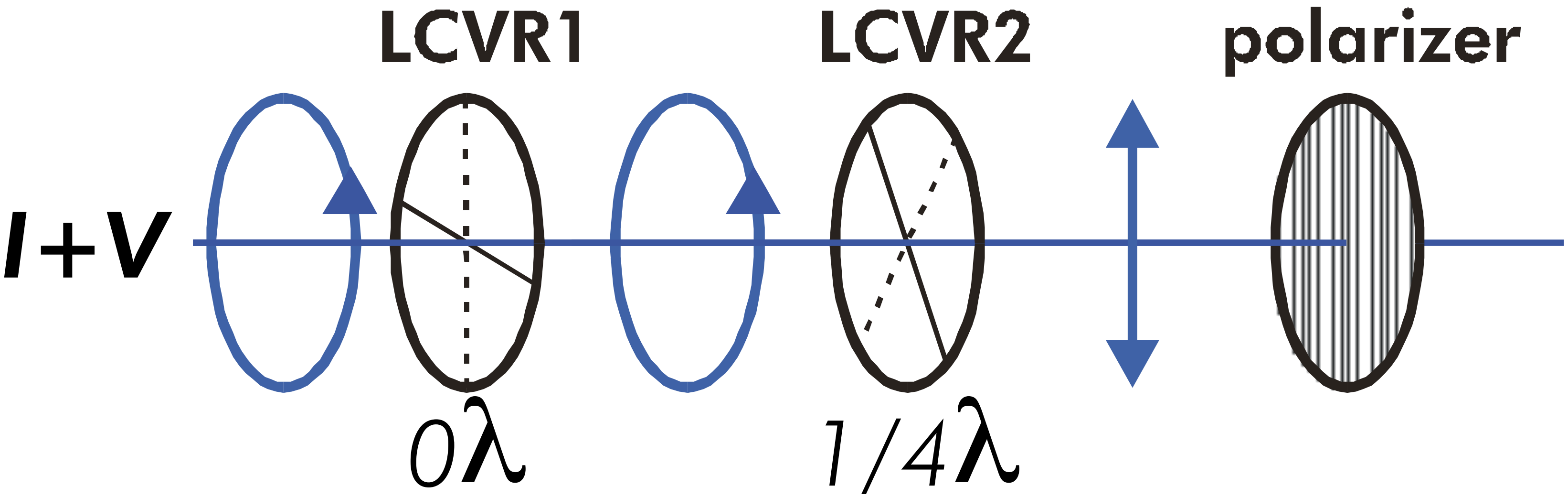
instruments

modulation & demodulation



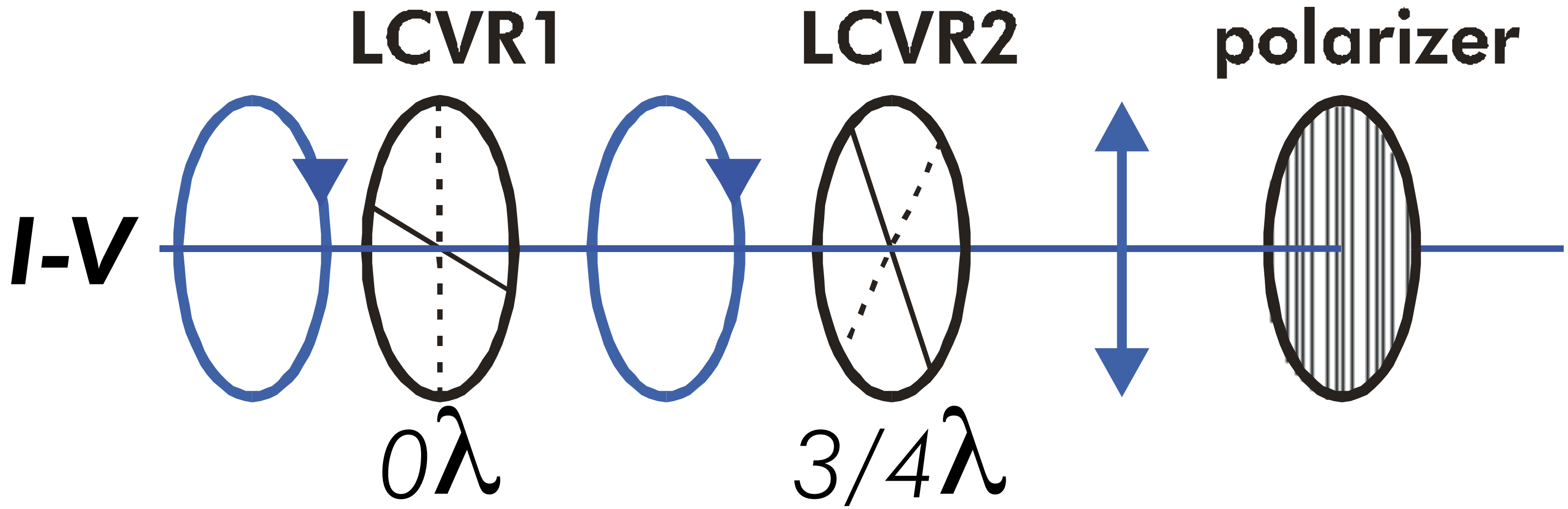
instruments

modulation & demodulation

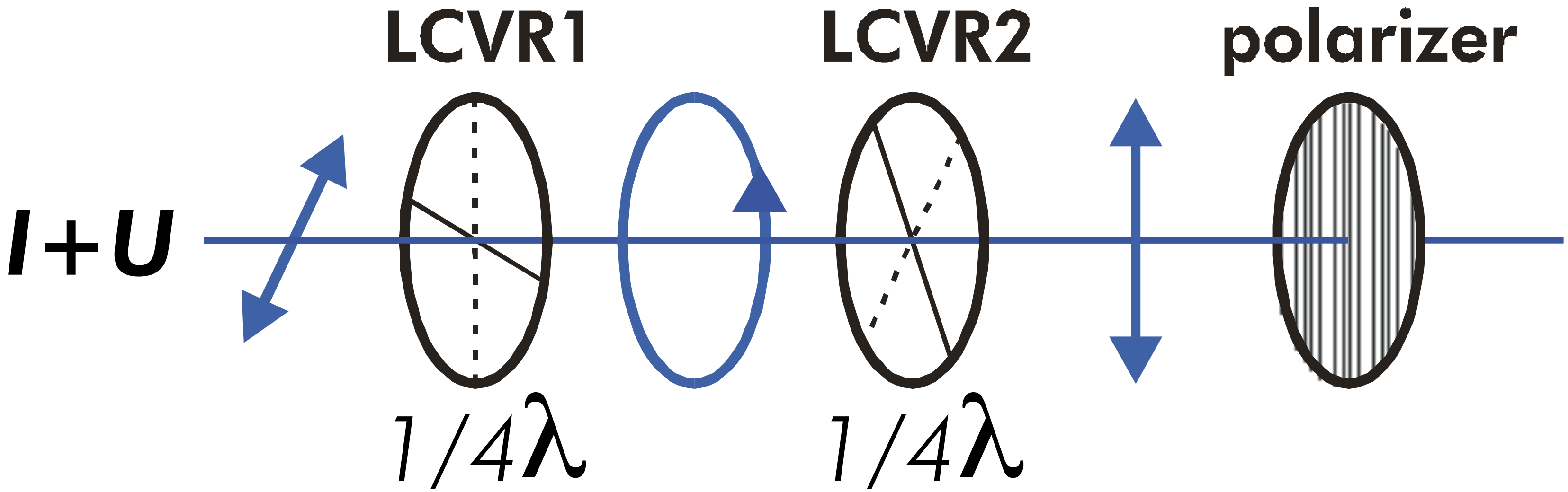


instruments

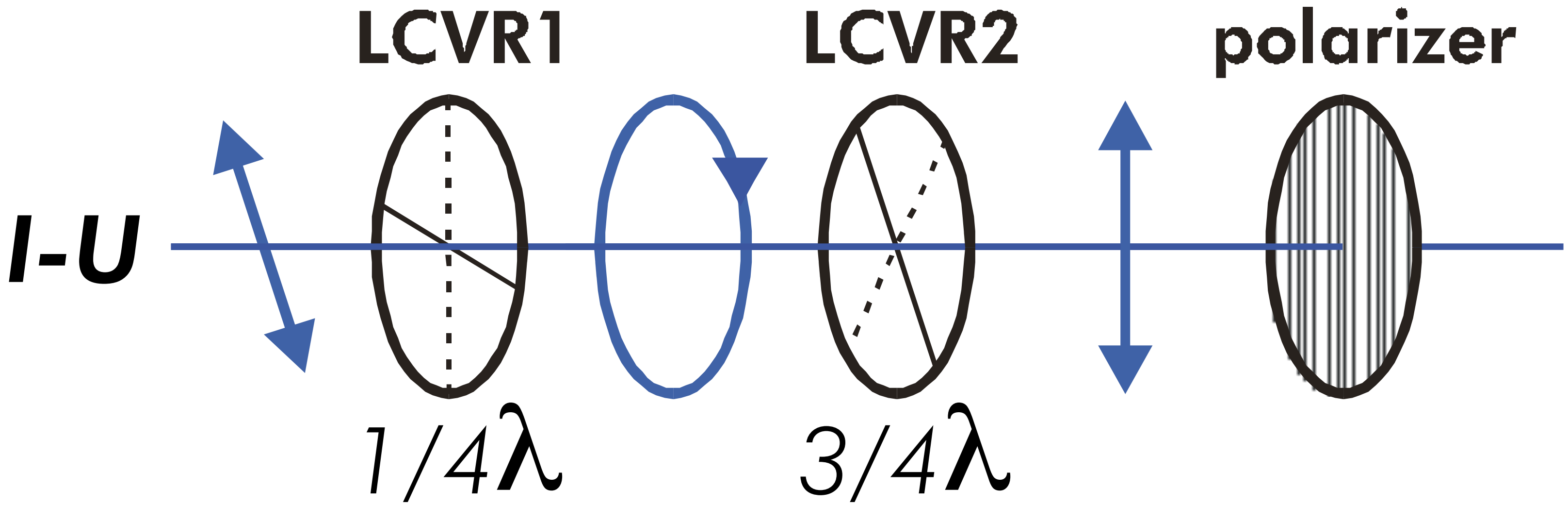
modulation & demodulation



modulation & demodulation



modulation & demodulation



•also complicated 4-fold modulation scheme

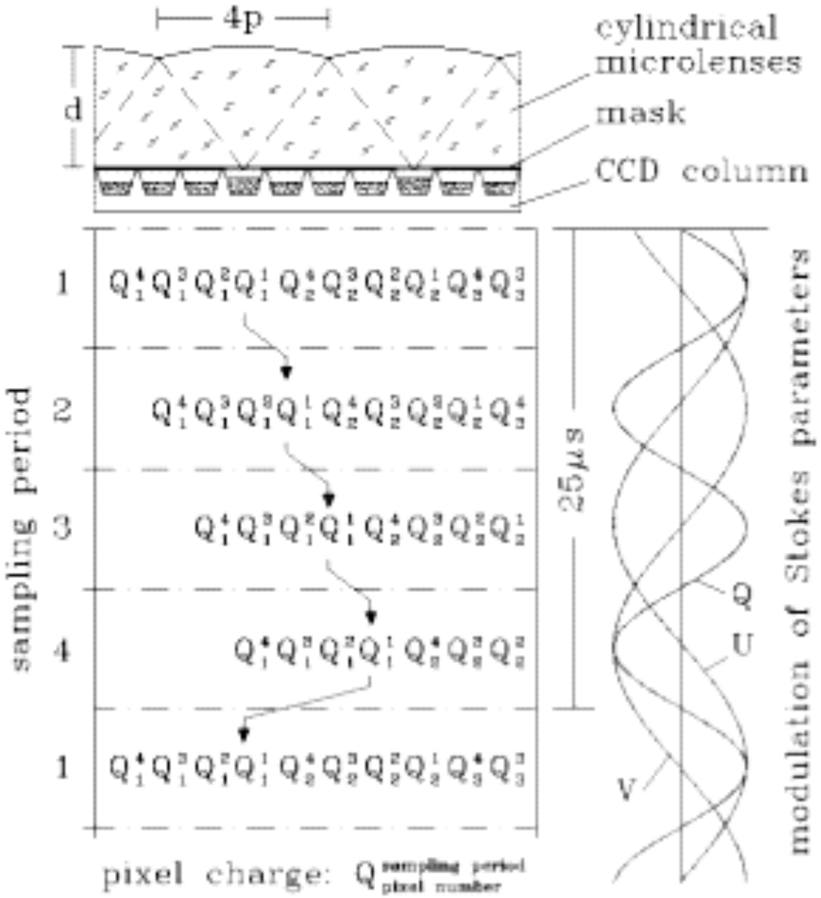
modulation & demodulation

- temporal modulation faster than seeing

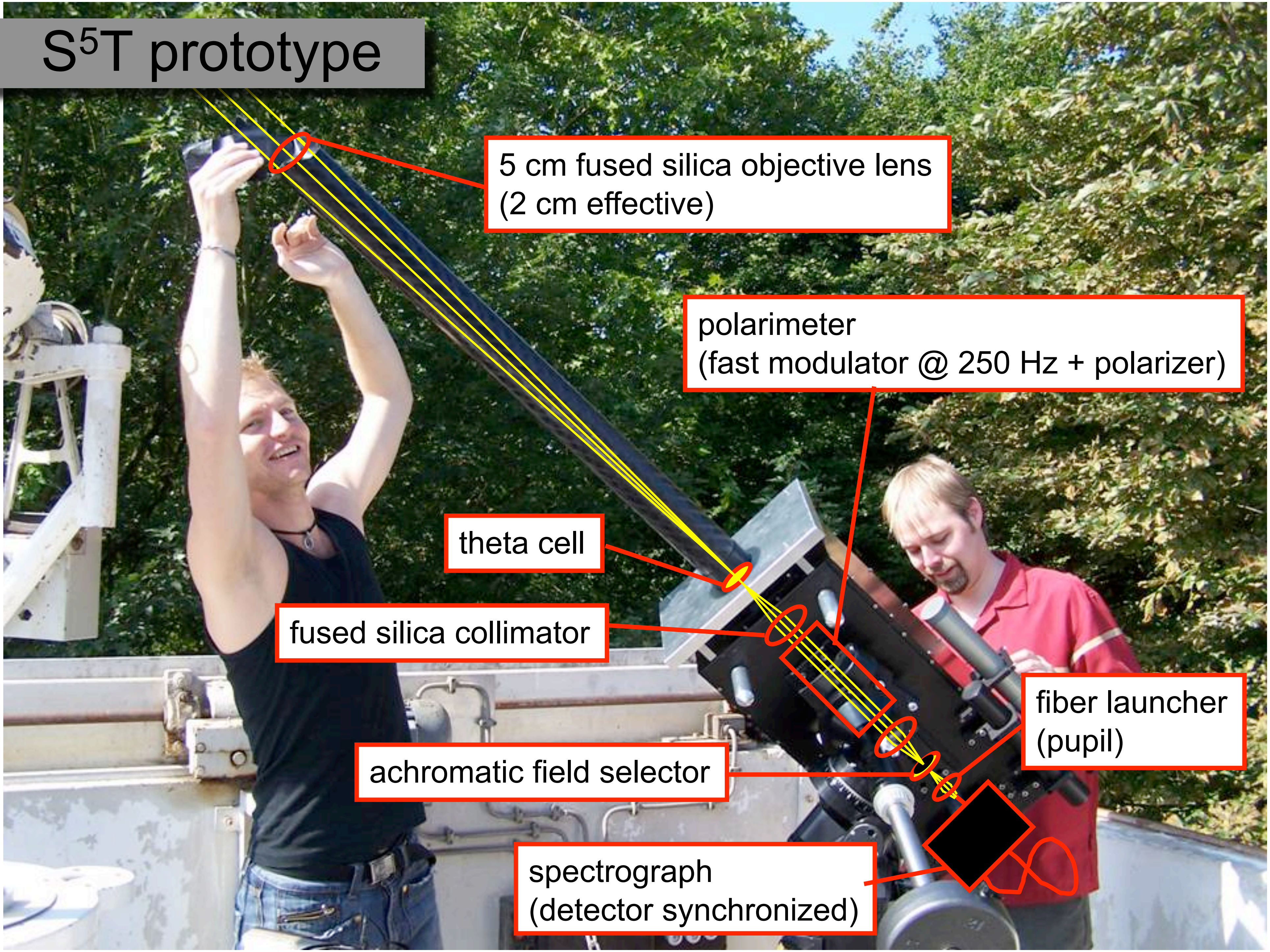
→ demodulating camera

ZIMPOL

10^{-5} polarimetric sensitivity



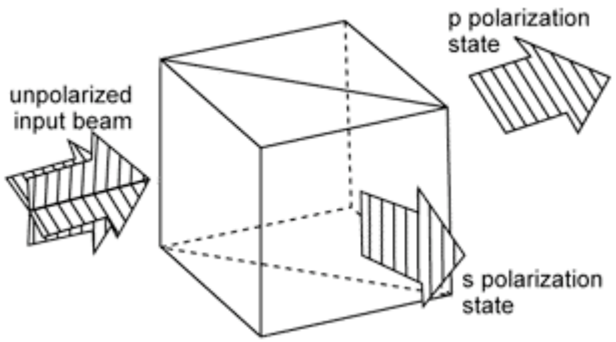
S⁵T prototype

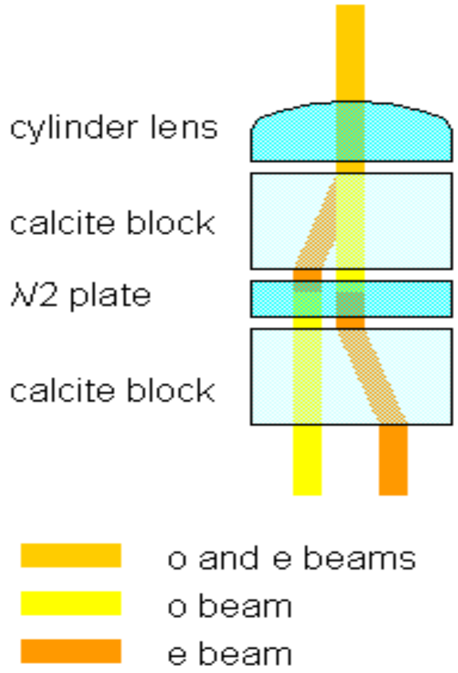


instruments

modulation & demodulation

spatial modulation with synchronous detectors





modulation & demodulation

- Dual beam: best of both worlds: spatial & temporal modulation: rotating wave plate + polarizing beam-splitter.

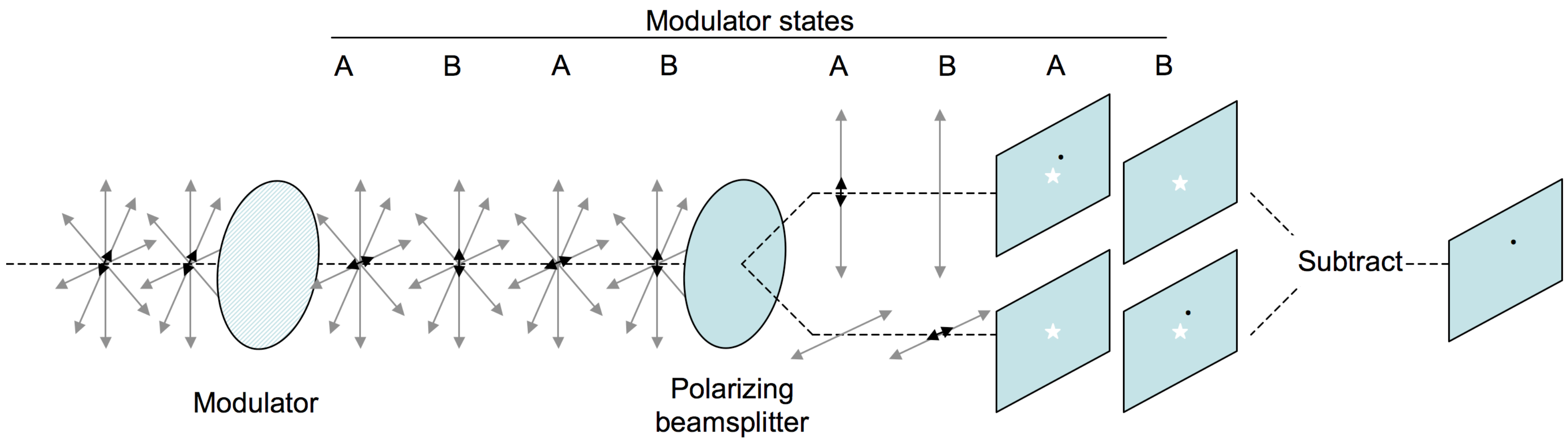
	L	R
$t = 1$	$I + V$	$I - V$
$t = 2$	$I - V$	$I + V$

$$\frac{1}{4}\left(\frac{S_1^L}{S_2^L}\frac{S_2^R}{S_1^R} - 1\right) \approx \frac{1}{2}\left(\frac{V_1}{I_1} + \frac{V_2}{I_2}\right)$$

Seeing effects and gain table effects drop out to first order!

instruments

modulation & demodulation



courtesy: M. Rodenhuis

instrumental polarization

- every reflection polarizes...
- every piece of glass is birefringent...

...to some degree

- careful design
  - rotationally symmetric
  - 90° compensations
- calibration!

limitations to polarimetry

- photon noise
- read noise
- seeing
- guiding errors
- scattered light
- instrumental polarization
- cross-talk
- fringing
- chromatism
- temperature dependence
- etc.

exercises

- 3.11
- 3.12
- 3.16
- Show that a wave-plate with its axes at 0 and 90 degrees does not do anything to incoming Stokes Q (defined ± as linear polarization at and 90 degrees). Why is this?
- At what time of the day does the telescope of Fig. 3.15 have minimal instrumental polarization? Show with a calculation.