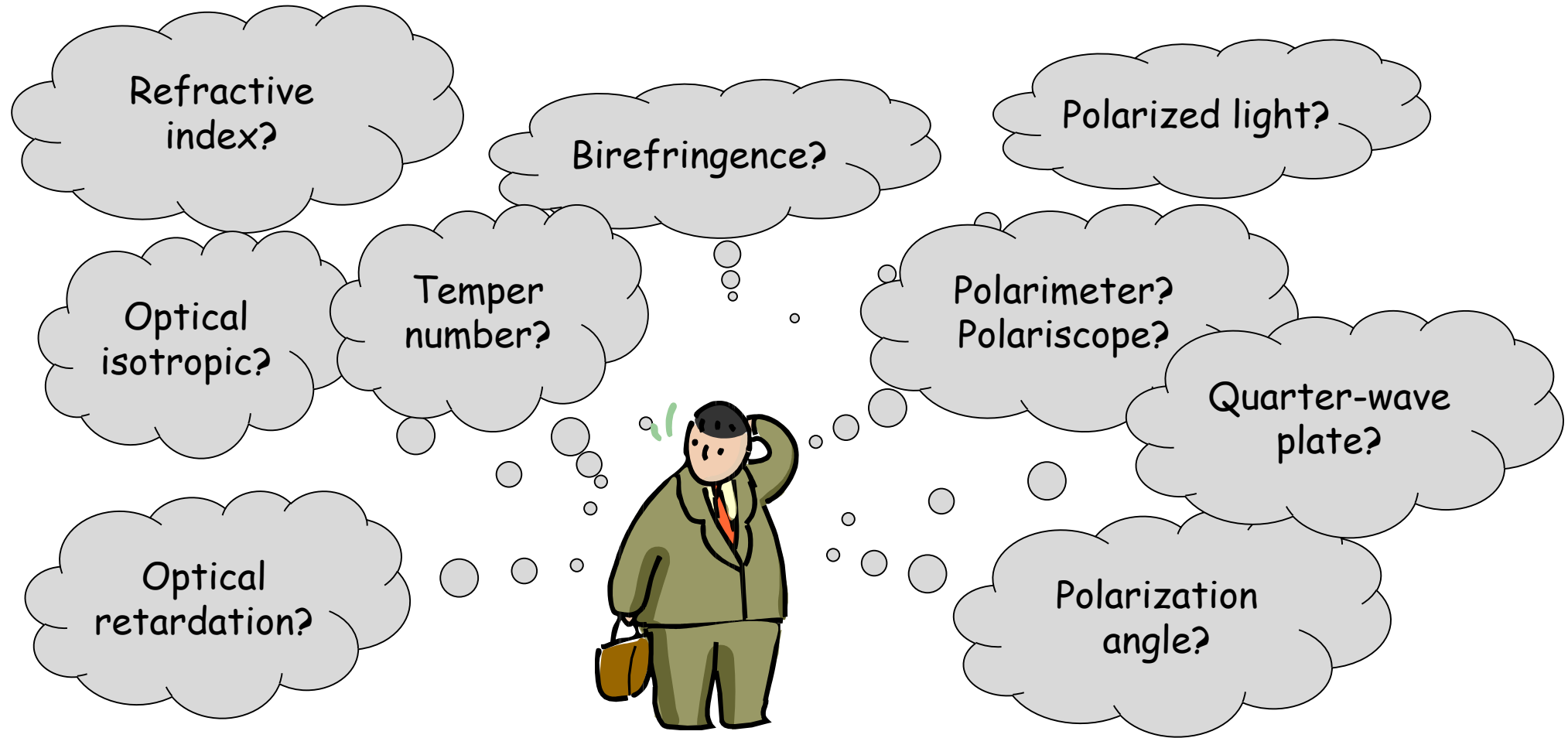# Basics of Photoelasticity

**Henning Katte**

ilis gmbh, Erlangen

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What is "Stress"?

- Mechanical stress is a term from strength theory, a branch of technical mechanics. It is the force per unit area that acts in an imaginary section through a body, a liquid or a gas.

- The mechanical stress has the same physical dimension as the pressure, namely force per area. The pressure represents a special case of the mechanical tension.

- Pascal or Newton per square meter (1 Pa = 1 N/m²), as well as Megapascal or Newton per square millimeter (1 MPa = 10^6 Pa = 1 N/mm²) derived therefrom, are common in practice as a unit of measurement for mechanical stress.

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Light and Refractive Index

- **Light** is an electromagnetic wave that causes atomic shells to vibrate, which in turn generates light.

- The **velocity of light** in the material depends on the particle density.

- The **refractive index** is the ratio of the light velocities in the vacuum and in the material: n = c/v

- Ordinary glass: n ≈ 1.5

wavelength

zero-crossing

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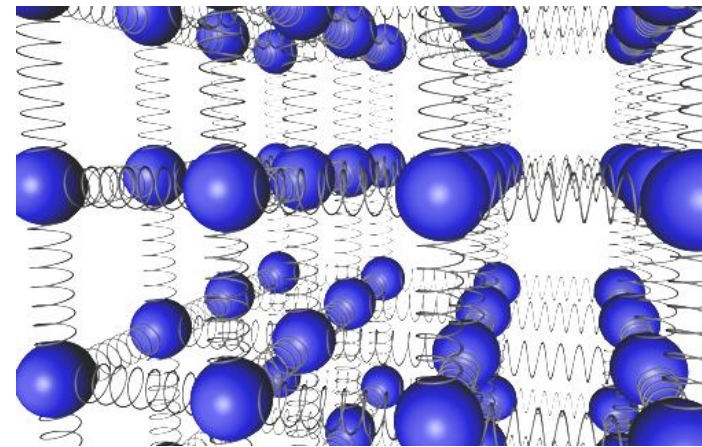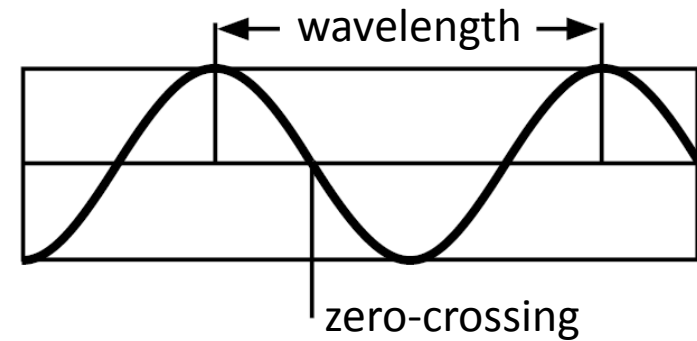
Stress Birefringence

- **Mechanical stress** leads to deformation of the material structure and therefore changes the particle density and the velocity of light.

- If the velocity of light (and therefore the refractive index) varies in different directions the material is called **birefringent**.

- Glass normally is **optically isotropic** but becomes birefringent when put under mechanical load
 ⇨ **stress birefringence**
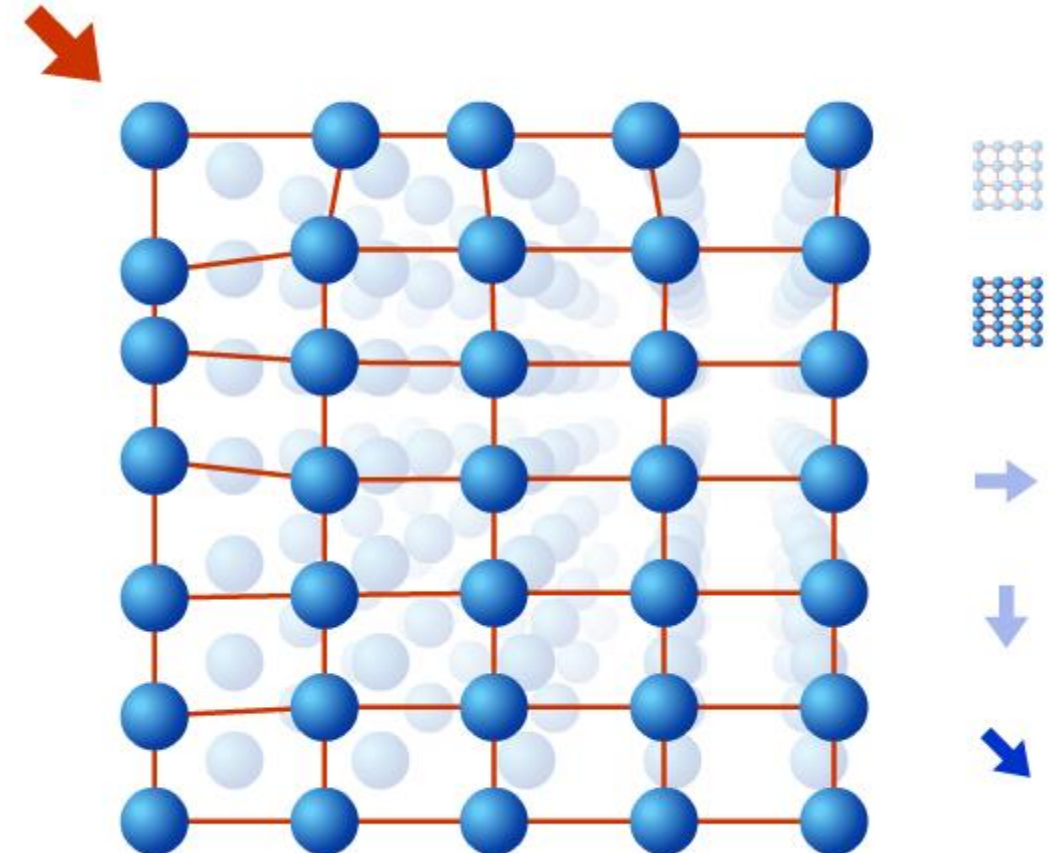
Linear Polarization of Light

- If the electric field of light oscillates only in one plane, this is called **linearly polarized light**.

- A (linear) **polarizer** lets pass only those light waves which are oriented parallel to its optical axis, thus producing linearly polarized light.
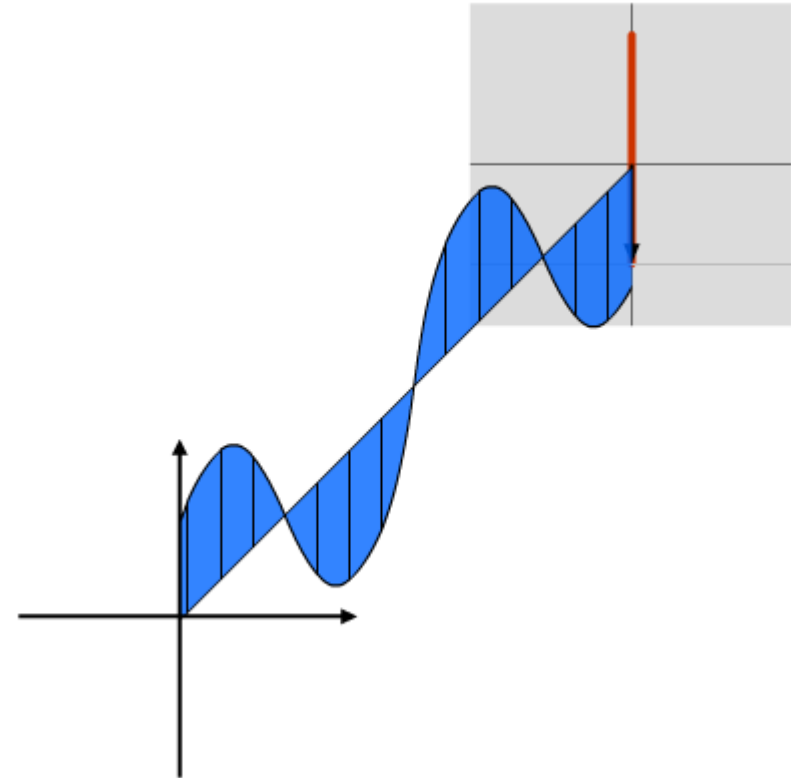
Circular and Elliptical Polarization

- In a birefringent material, the light waves propagate in horizontal and vertical directions at different speeds, resulting in an optical path difference or **optical retardation**.

- Linearly polarized light leaves a birefringent material as a superposition of two mutually perpendicular light waves of different phasing.

- If the optical retardation is exactly one quarter of the wavelength, the light is **circularly polarized**.

- In the general case, the emergent light is **elliptically polarized**.
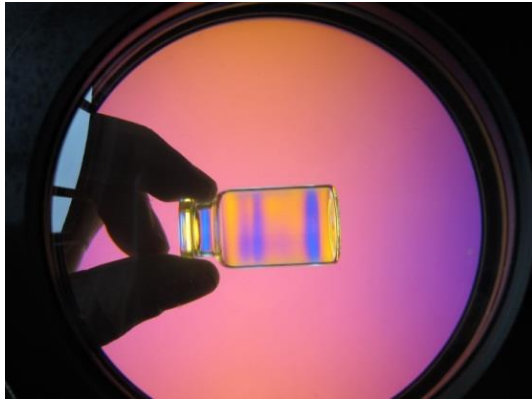
- The ellipticity is a measure of stress birefringence.

Optical Retardation

0   λ/4   λ/2
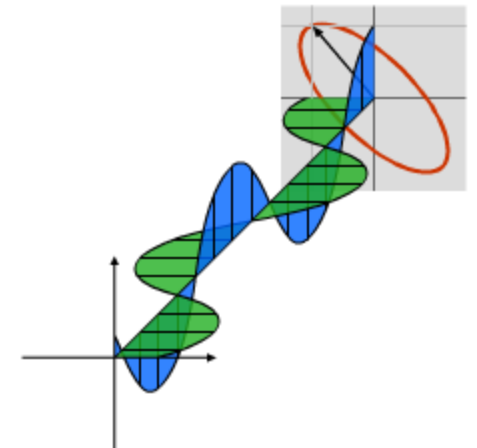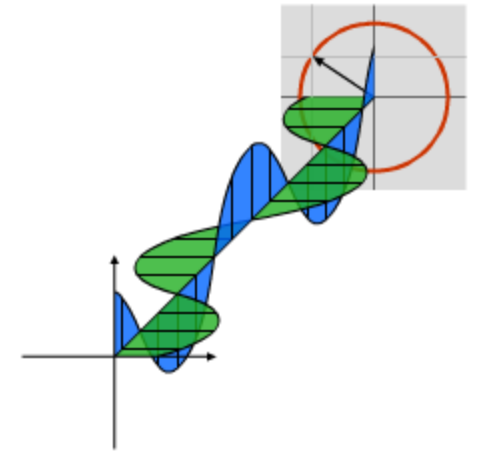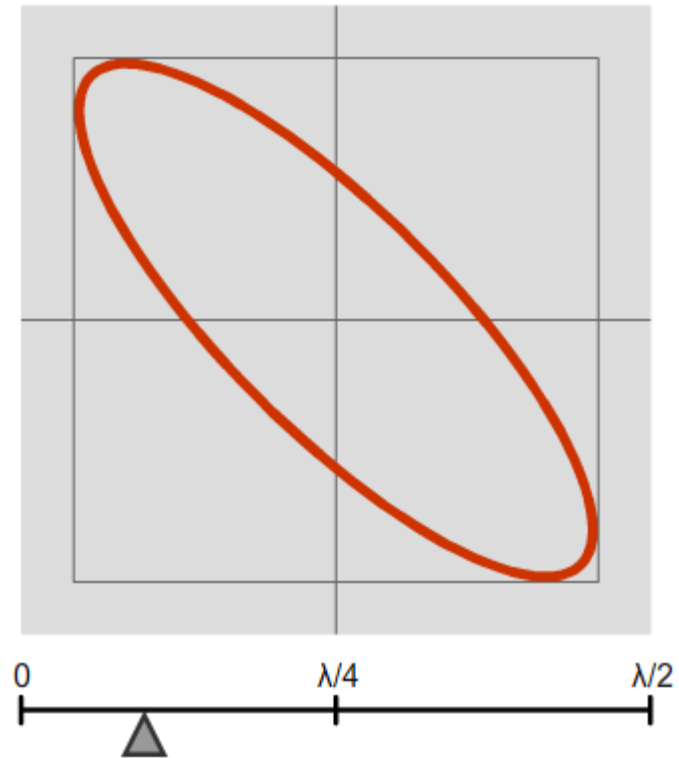
Relationship between ellipticity and optical retardation
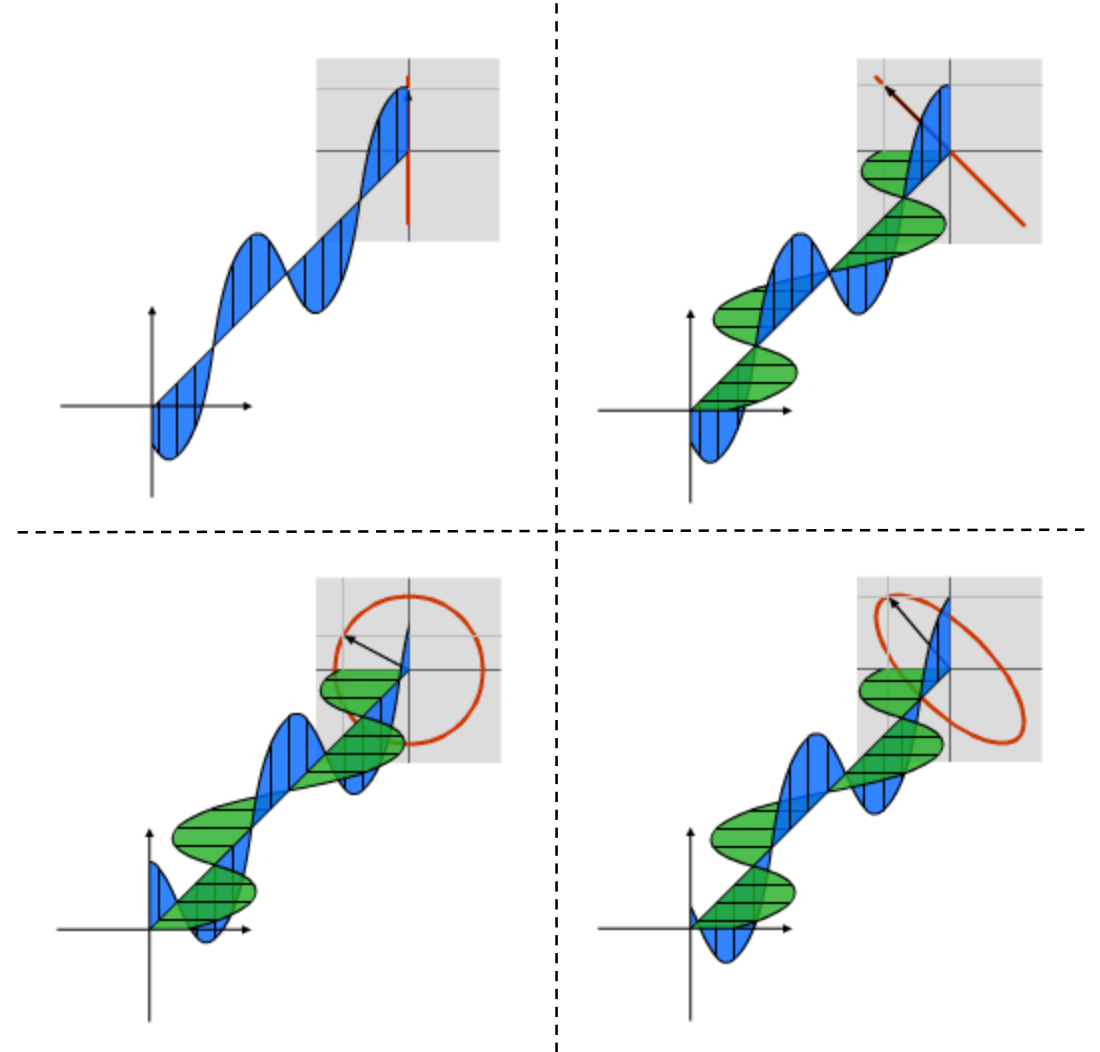
Polariscope vs. Polarimeter

Polariscopes visualize stresses based on interference colors (neutral areas red-violet, areas with stresses blue and yellow).

Polariscopes allow a quick assessment of stresses, but not an accurate measurement.

Polarimeters allow the measurement at a certain measuring point according to the Sénarmont method.
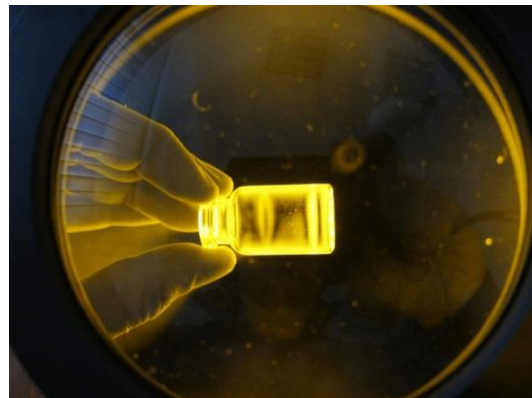
Polariscope – Structure and Working Principle

Detector

Polarizer (crossed)
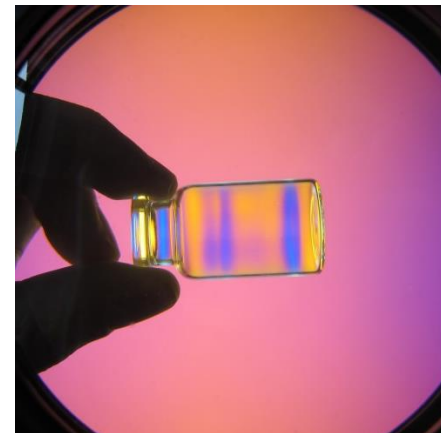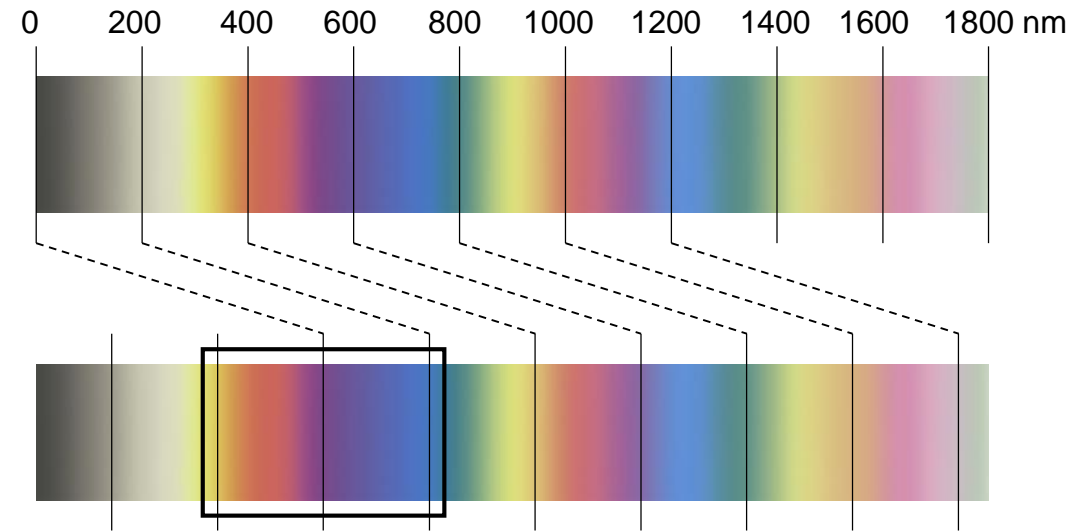
Full wave plate

Specimen

Polarizer
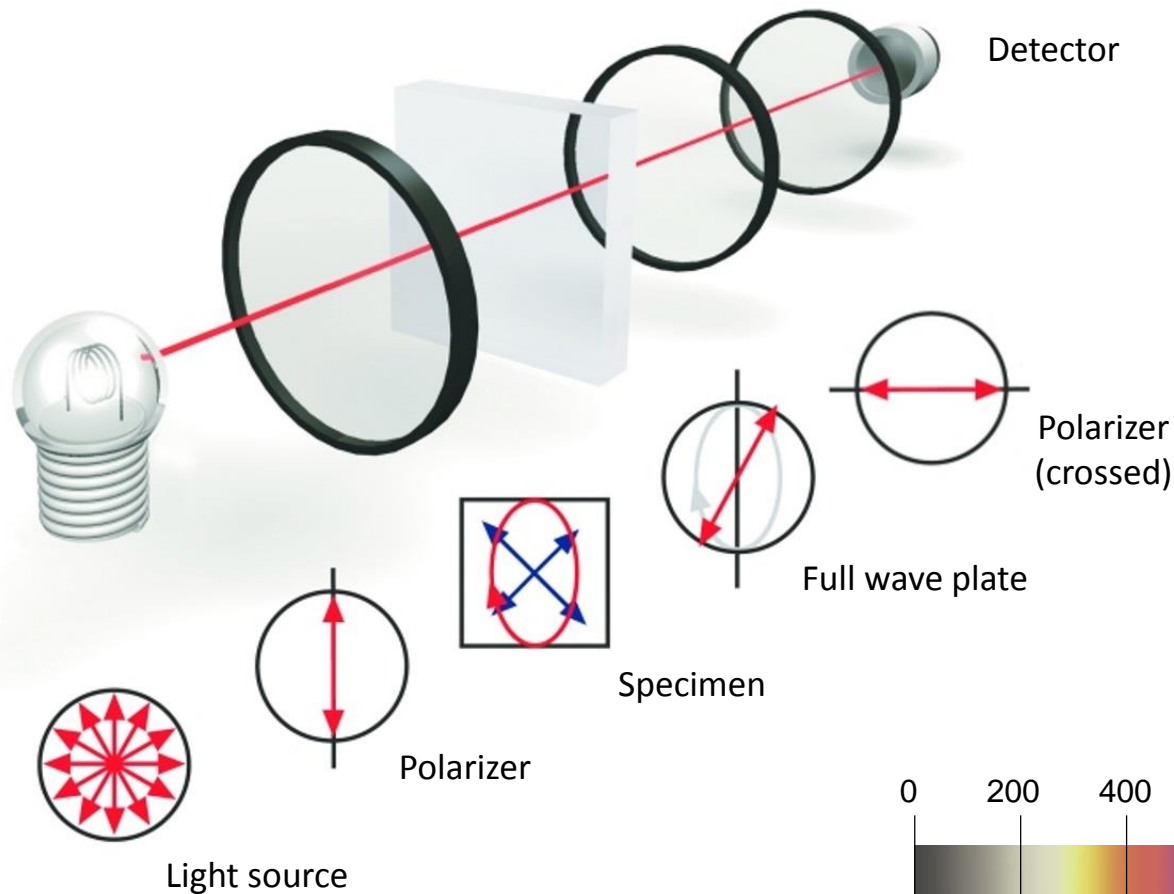
Light source

- **Polariscopes** with two crossed polarizers show colored images with birefringent materials and a white light source.

- Stress birefringence generates elliptically polarized light that partially passes the second polarizer. The degree of extinction depends on both birefringence and wavelength.

- If a color is filtered out of the spectrum, the remaining light assumes the complementary color. This interference color can be translated into retardations using color scales.

0   200   400   600   800   1000   1200   1400   1600   1800 nm
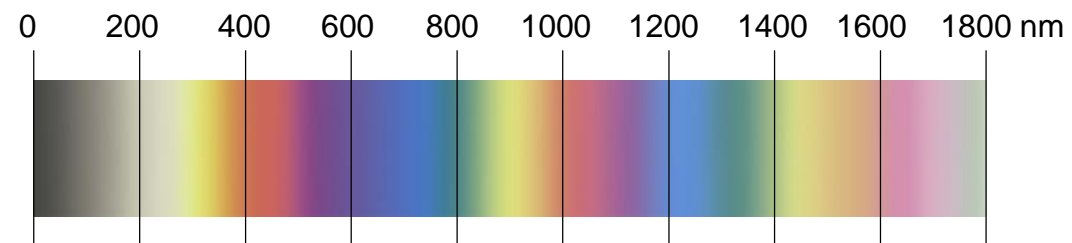
Full Wave Plate (1st Order Red Tint Plate)

- At low retardations (<300 nm), the image is not colored; different delays cause different gray levels.

- By adding a **full wave plate**, the retardation can be shifted to a region that is more easily evaluated, e.g. around 550 nm.

- Negative retardation then appear in yellow and positive values in blue. Neutral areas are red-purple.
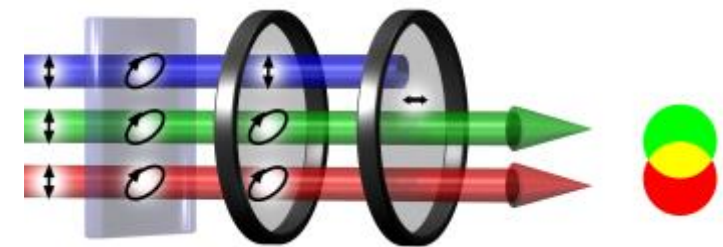
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Full Wave Plate – Explanation

a) Without a sample, the light does not change at 550 nm wavelength; However, light of other wavelengths is elliptically polarized and partially transmitted trough the polarizer. The spectrum without green light is red-blue (**violet**).

b) If a further retardation (for example 550 + 100 = 650 nm) is added by the strained sample, red light is filtered out, so the residual light is **turquoise**.

c) If the retardation through the sample is negative (e.g., tensile stress instead of compressive stress), then a **yellow** color appears instead of turquoise
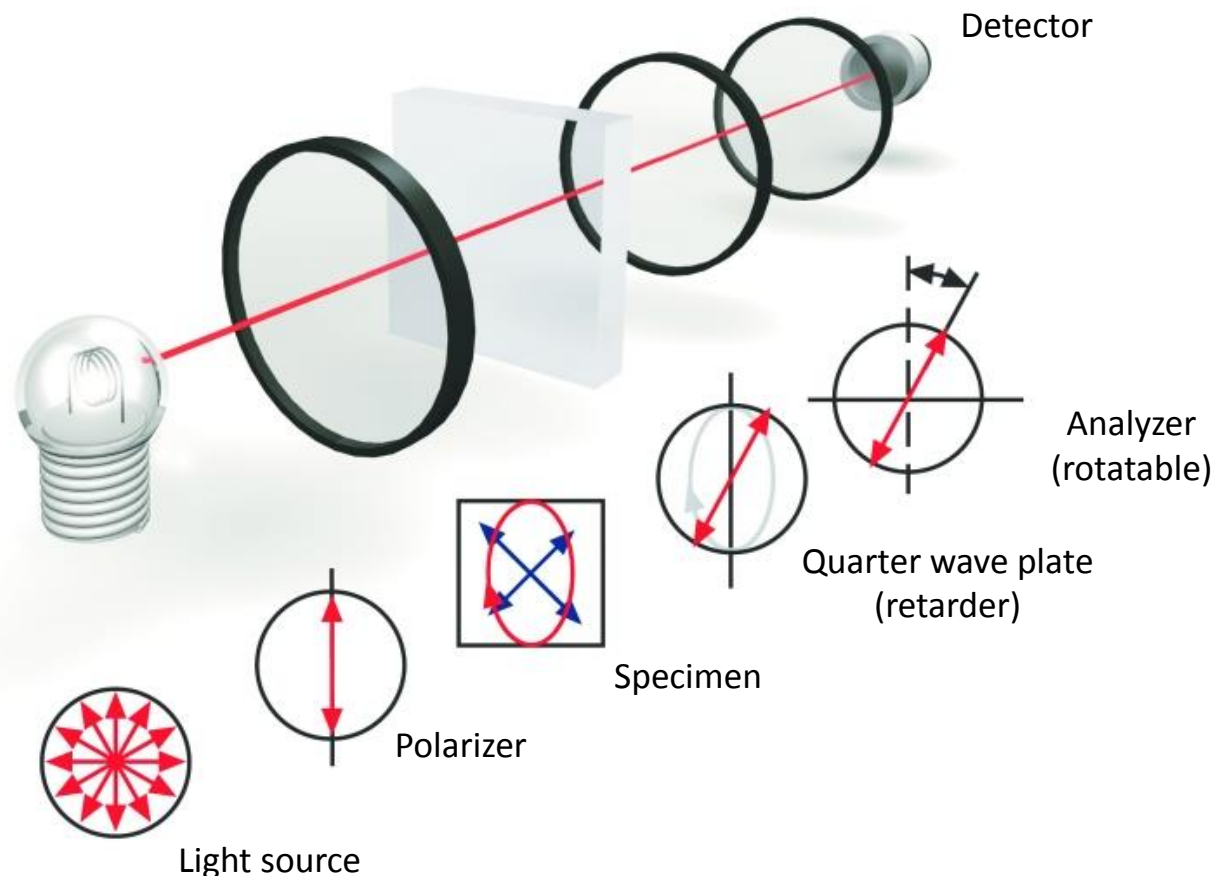

full wave plate   polarizer
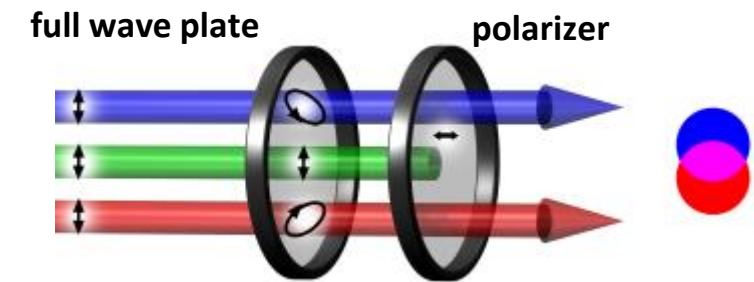
a) Without sample
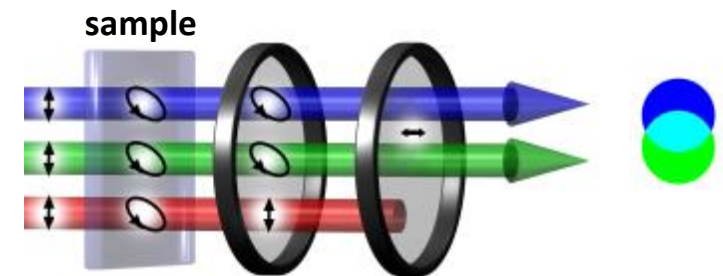
sample

b) Sample with positive retardation

c) Sample with negative retardation

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Polarimeter – Structure and Working Principle


Detector

Analyzer
(rotatable)

Quarter wave plate
(retarder)

Specimen

Polarizer

Light source

- The polarimeter structure is very similar to the polariscope design, but instead of a full wave plate, a **quarter wave plate** is used and the second polarizer (analyzer) is rotatable.

- A quarter-wave plate consists of birefringent material and produces a path difference of one quarter of the wavelength (hence $\lambda/4$ plate).

- Linearly polarized light, which incidents at an angle of 45° to the optical axes, is converted into circularly polarized light.

- Conversely, elliptically polarized light is converted back into linearly polarized light by the $\lambda/4$ plate, but with a different polarization angle.

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Polarimeter – Sénarmont Measuring Principle

- When viewed through a polarizer crossed to the original polarization direction, strained parts of the sample appear as brightened areas in the otherwise black field of view.

- The **polarization angle** describes the ellipticity of the light emerging from the sample, and is therefore a measure of the birefringence and thus of the stress in the material.

- The polarization angle is measured by turning the analyzer until the brightened area is darkest.

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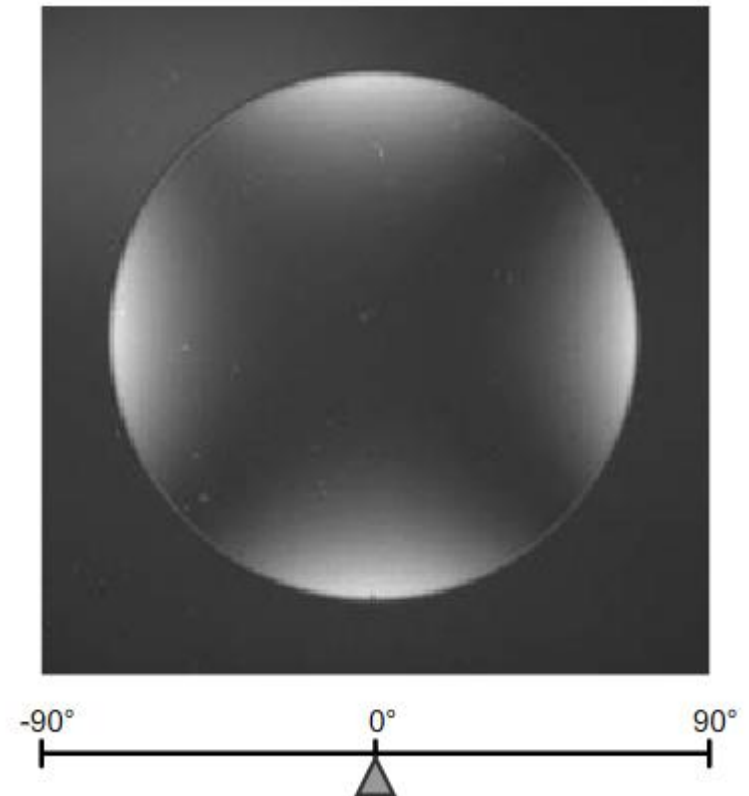
Polarimeter – Illustration

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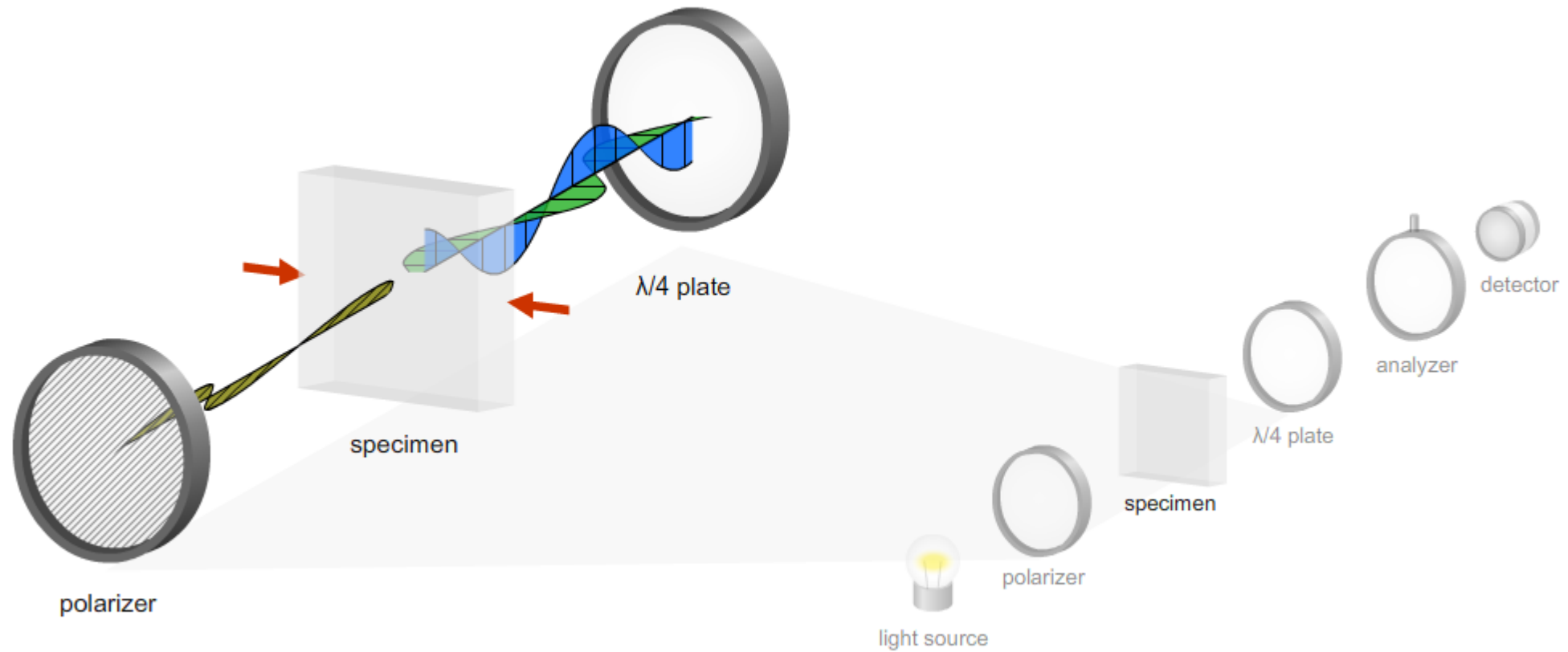
Common Measurements Units

- From the polarization angle α, the **optical retardation** R in nm can be calculated according to the following formula:

  $R = \alpha \cdot \lambda / 180°$ (λ = used wavelength in nm)

- If the birefringence along the measuring beam is homogeneous, the **normalized optical retardation** N in nm/cm can be calculated:

  $N = R \cdot (10 / d)$ (d = sample thickness in mm)

- In the case of membrane stresses (and only then), the optical retardation can be converted to **stress** S in MPa as long as the photoelastic coefficient (a material constant) is known:

  $S = R / (d \cdot C)$ (C = photoelastic coefficient in TPa^{-1})

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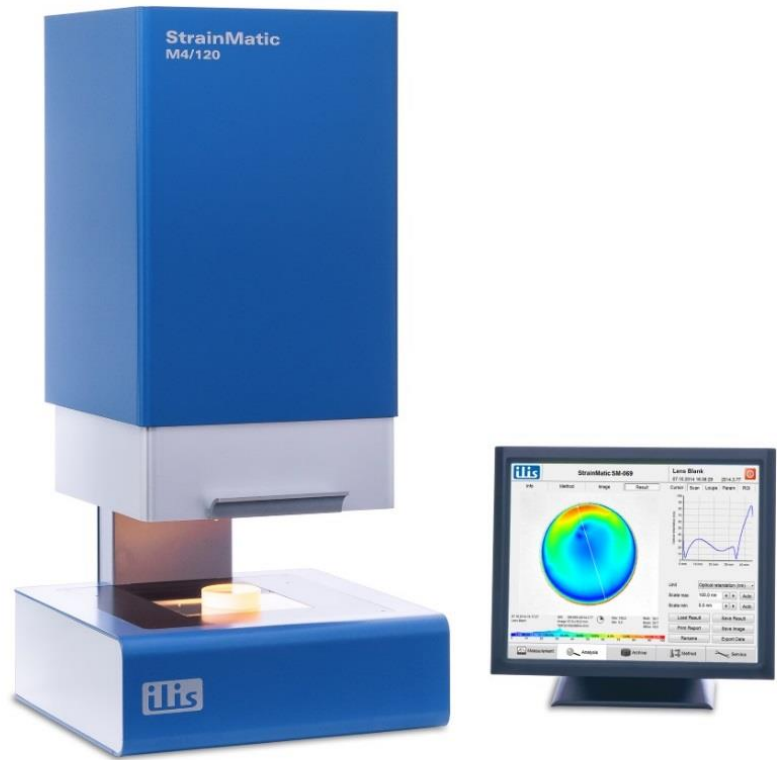# Temper Number (ASTM C 148)

- To quantify residual stresses in container glasses, the US standard ASTM C 148-00 defines the **apparent temper number** unit, which is based on the optical retardation of a so-called strain disk (which was originally used for visual comparison):

$$T_A = R \, / \, 22.8 \text{ nm}$$

- Taking into account the thickness of the sample (base or wall thickness) *d*, the apparent temper number can be converted into the real **temper number**:

$$T_R = T_A \cdot (4.06 \text{ mm} \, / \, d) = (R \, / \, 22.8 \text{ nm}) \cdot (4.06 \text{ mm} \, / \, d)$$

Automatic Imaging Measurement

- Automatic determination of the polarization angle for each pixel (Sénarmont method)

- Color-coded representation of the measured values

- Combination of multiple measurements under different polarizations to avoid "blind spots" and determine the stress orientation

StrainMatic® imaging polarimeter system
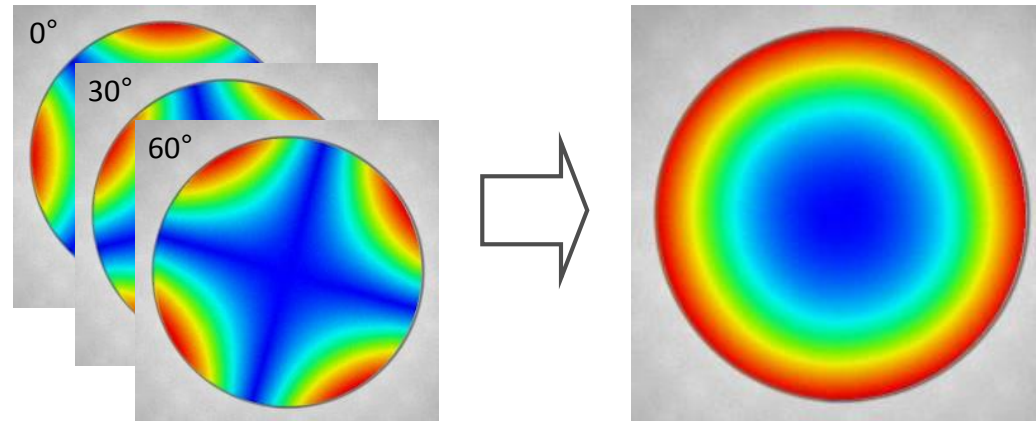
# Continuous Measurement in Real Time

- Rotatable analyzer replaced by a special polarization camera with no moving elements

- Measurement in real time (20 Hz), also on moving objects and directly in the process

- Measurement with circularly polarized light allows determination of correct magnitude and orientation of the stresses
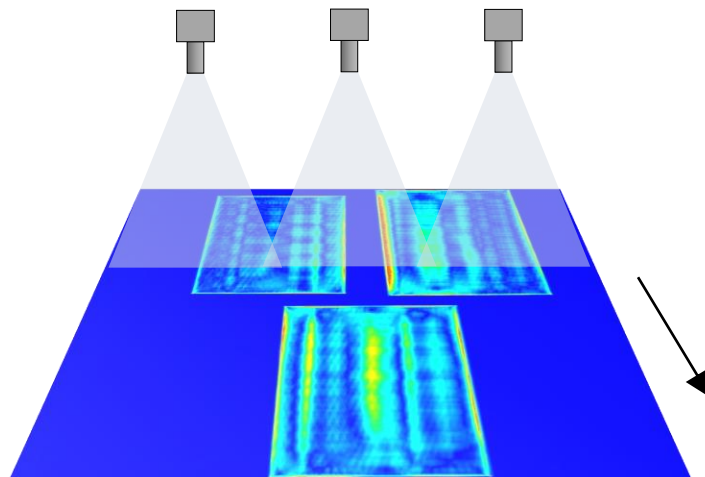
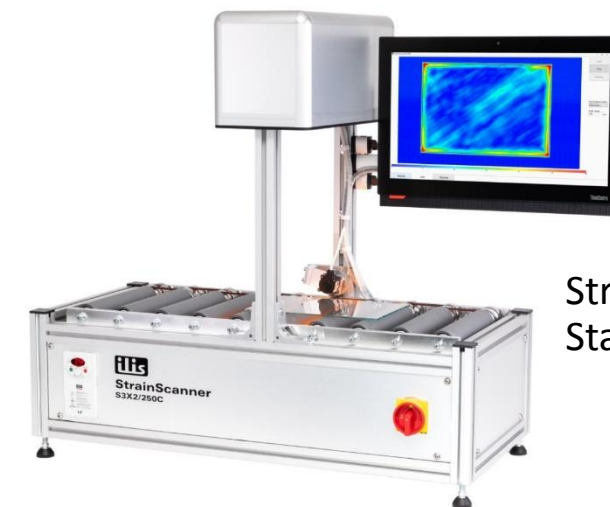StrainScope® real time polarimeter
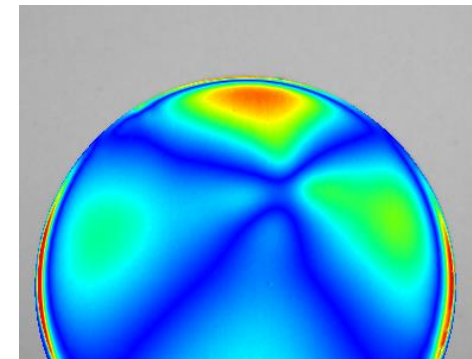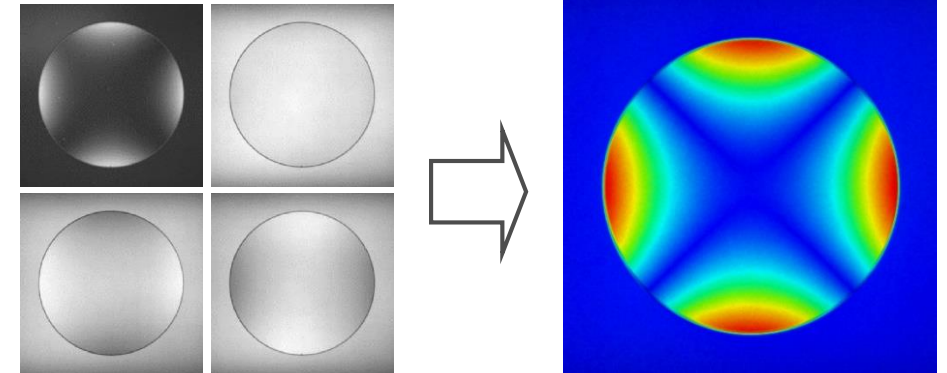
linearly polarized   circularly polarized

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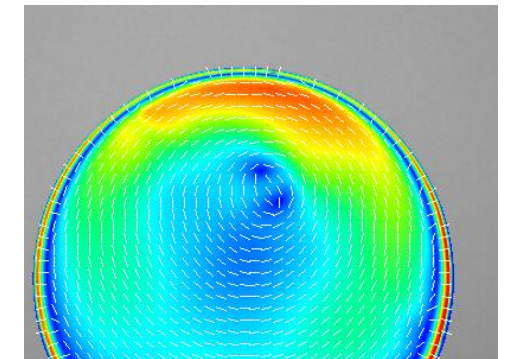
Scanning Measurement

- Measurement of stresses and optical anisotropies in large-format objects

- Several cameras continuously scan the passing objects

- The overall result is automatically composed of countless single images

StrainScanner™ Inline polarimeter

StrainScanner™ Standalone

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