

Aachen Polymer Optics Days

Online Session IV: Metrology of optical components

September 1, 2021

Fast and Objective Measurement of Material Stresses in Polymer Optics

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Overview

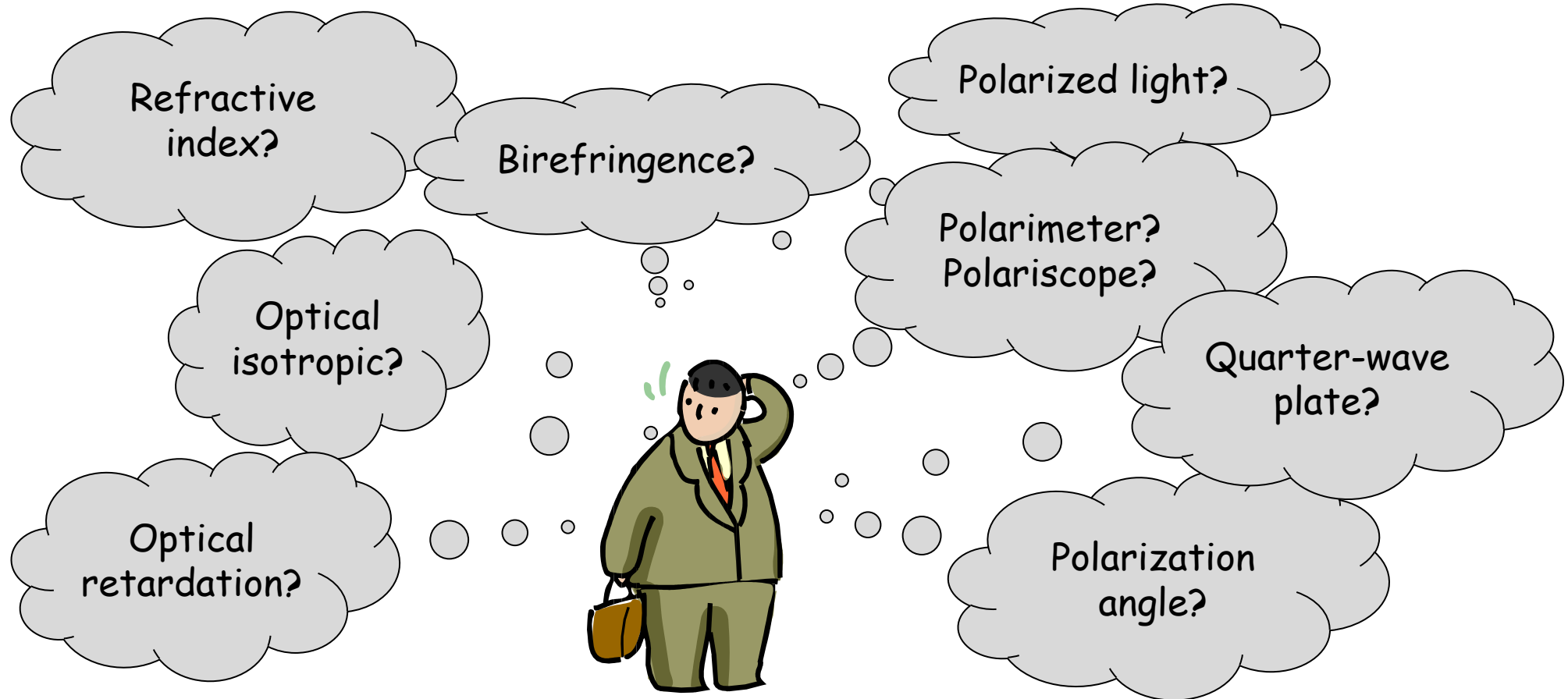
- Company introduction
- Basics of photoelasticity
- Manual measurement
- Automatic measurement
- Measurement of polymer materials

ilis gmbh



- Founded 1998, based in Erlangen, Germany
- Competencies
stress measurement, color measurement, batch calculation
- Target markets
glass industry, optics & photonics, automotive, aerospace, pharma
- Applications
container glass, flat glass, tableware, tube and laboratory glass, pharmaceutical packaging, optical materials and components, transparent plastics
- Products and brands
BatchMaker[®], Chroma[™], StrainMatic[®], StrainScope[®], StrainScanner[®], StrainCam[®]

Basics of Photoelasticity

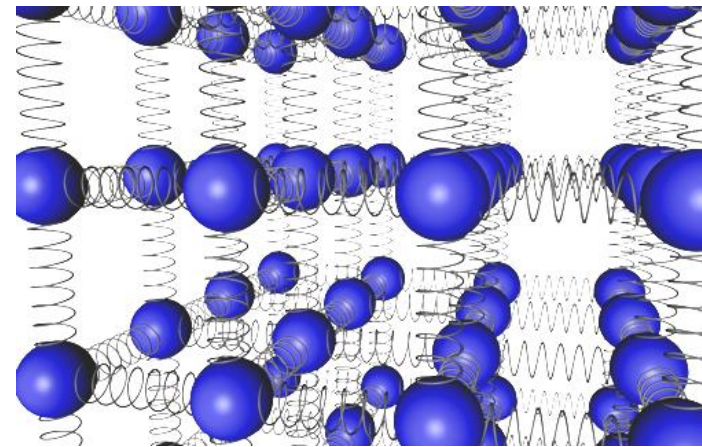
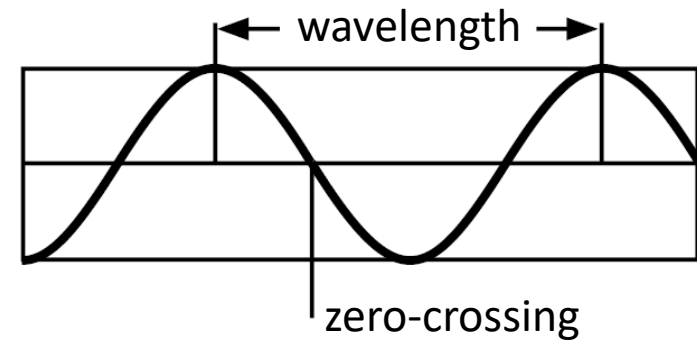


What is “Stress”?

- 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 ($1 \text{ Pa} = 1 \text{ N/m}^2$), as well as Megapascal or Newton per square millimeter ($1 \text{ MPa} = 10^6 \text{ Pa} = 1 \text{ N/mm}^2$) derived therefrom, are common in practice as a unit of measurement for mechanical stress.

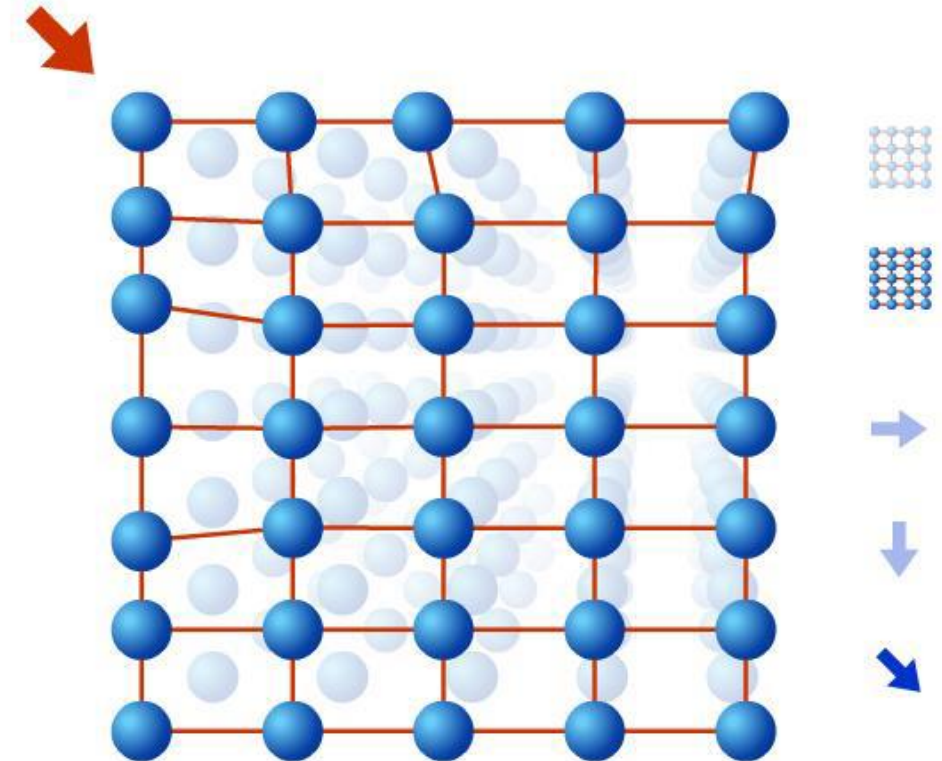
Light and Refractive Index

- **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 or plastics: $n \approx 1.5$



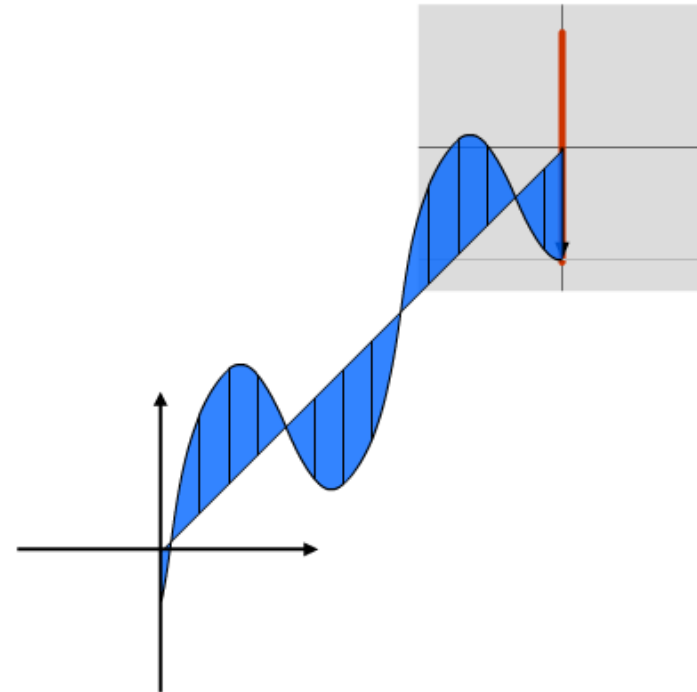
Stress Birefringence

- **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**.
- Materials that are normally **optically isotropic** become birefringent when put under mechanical load
⇒ **stress birefringence**



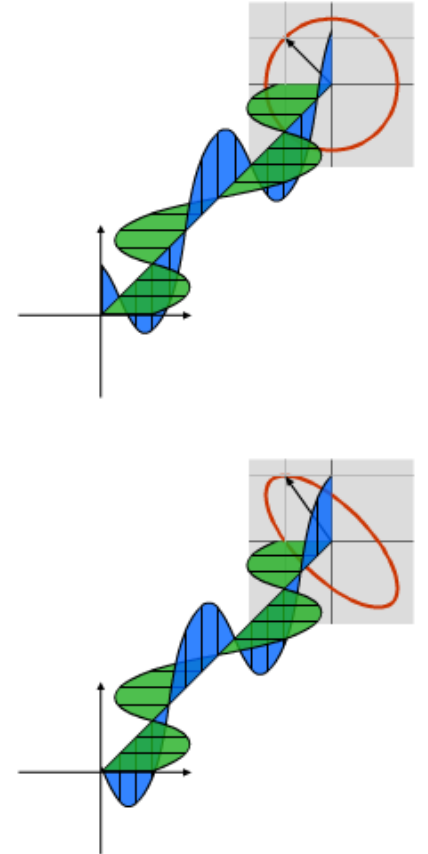
Linear Polarization of Light

- 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.

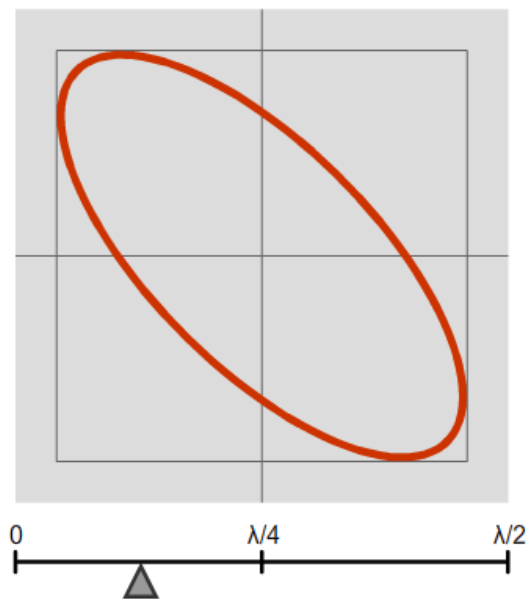


Circular and Elliptical Polarization

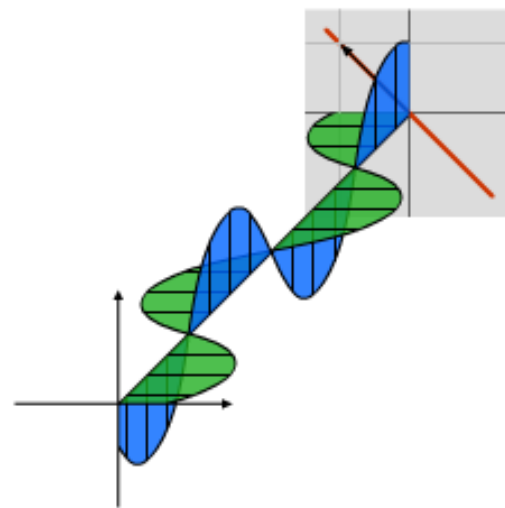
- In a birefringent material, the light waves propagate in horizontal and vertical directions at different speeds, resulting in an optical path difference or **optical retardation**.
- Linearly polarized light leaves a birefringent material as a superposition of two mutually perpendicular light waves 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.



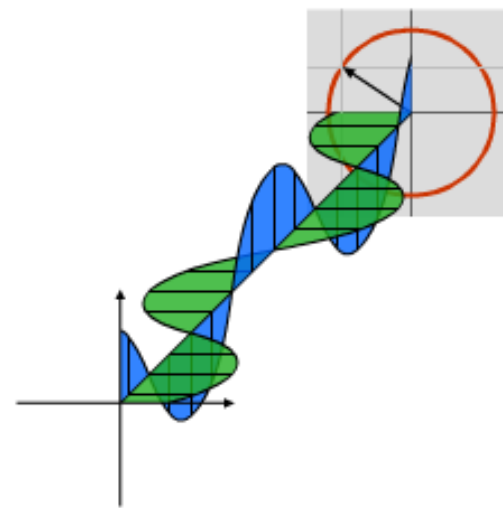
Optical Retardation



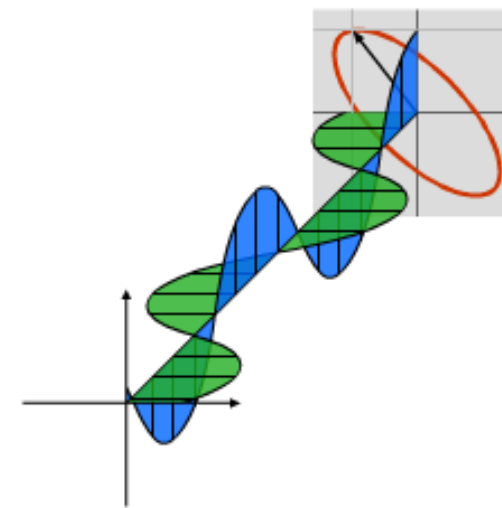
Relationship between ellipticity and optical retardation



Retardation = 0
 \Rightarrow Linear polarization

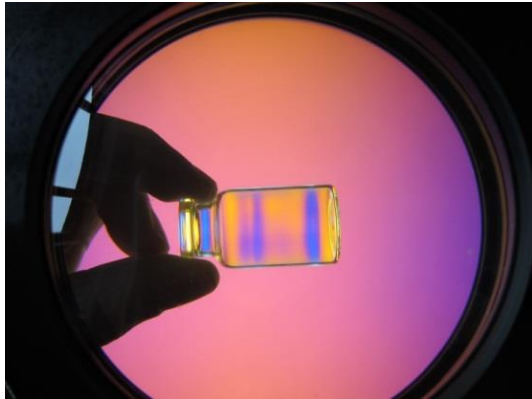


Retardation = $\lambda/4$
 \Rightarrow Circular polarization



Retardation = $\lambda/8$
 \Rightarrow Elliptical polarization

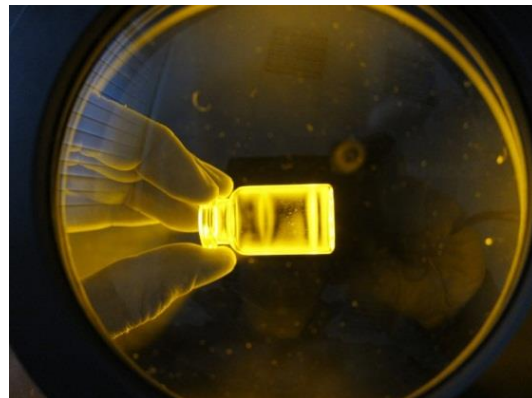
Manual Measurement with Polariscopes & Polarimeters



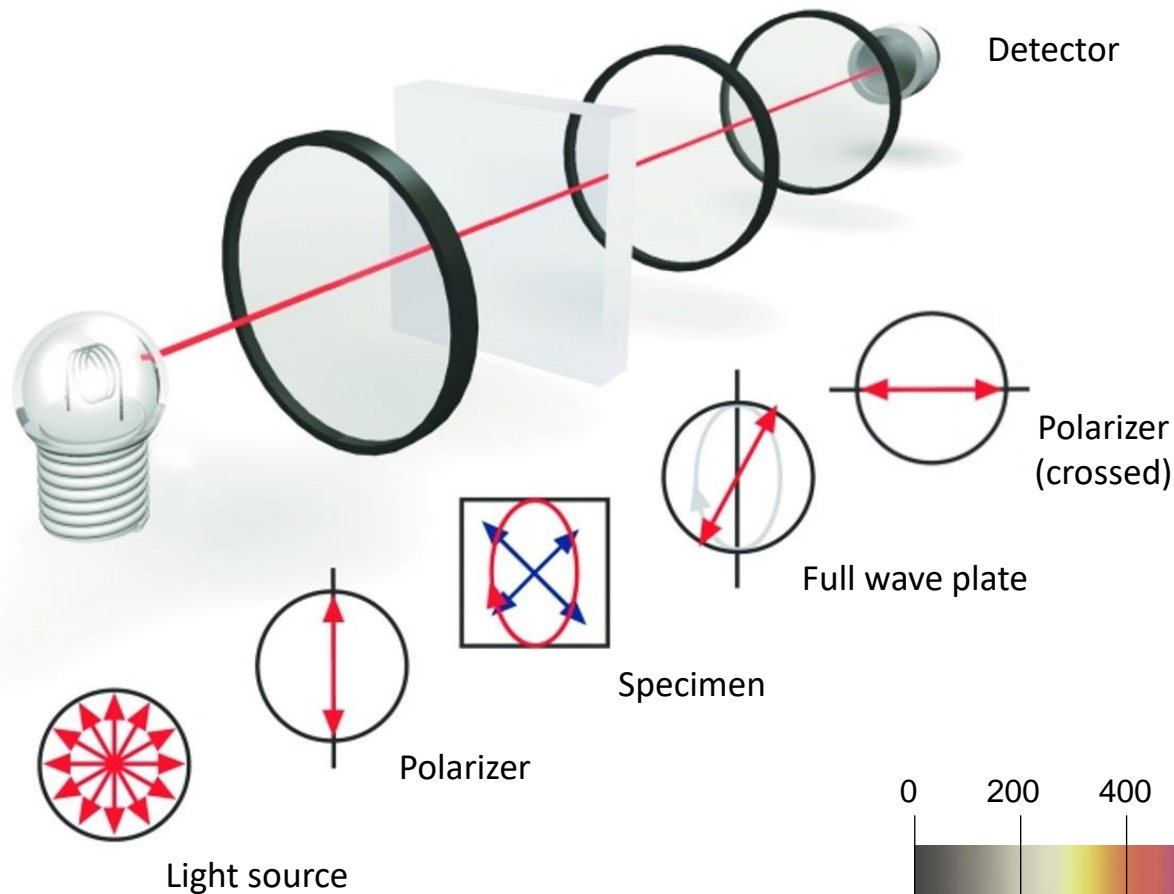
Polariscopes visualize stresses based on interference colors (neutral areas red-violet, areas with stresses blue and yellow).

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

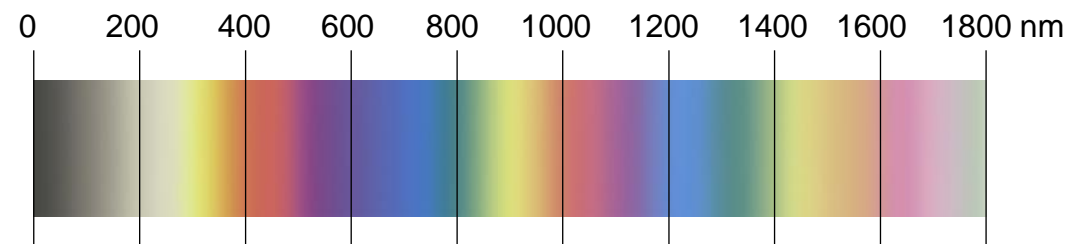
Polarimeters allow the measurement at a certain measuring point according to the Sénarmont method.



Polariscope – Structure and Working Principle

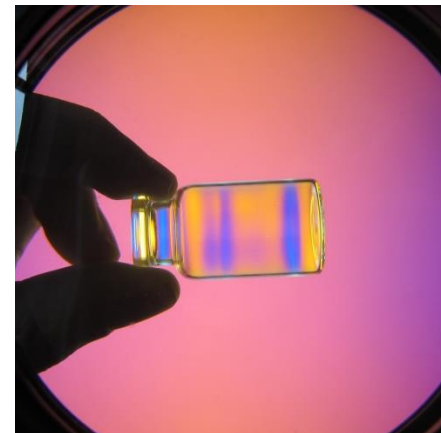
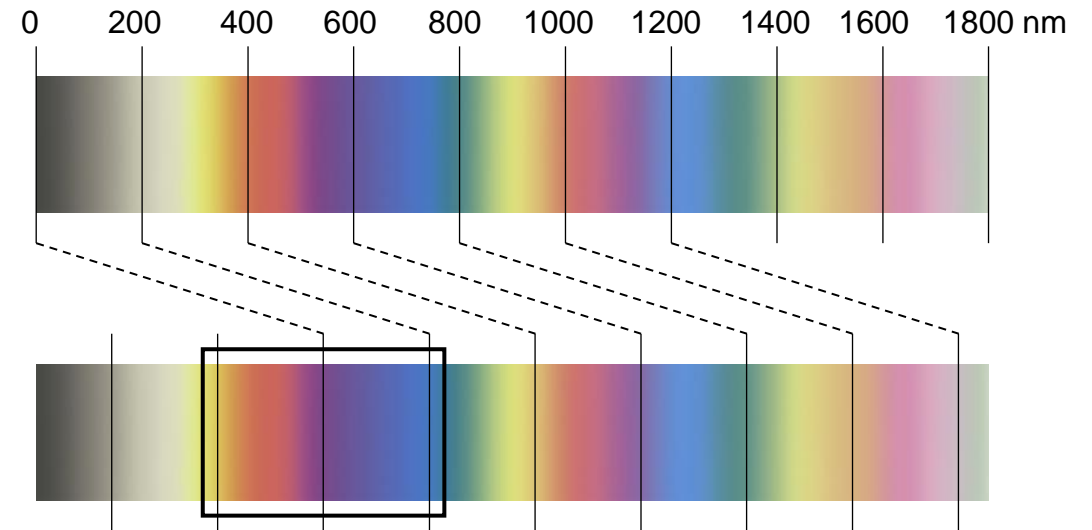


- **Polariscopes** with two crossed polarizers show colored images with birefringent materials and a white light source.
- Stress birefringence generates elliptically polarized light that partially passes the second polarizer. The degree of extinction depends on both birefringence and wavelength.
- If 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.



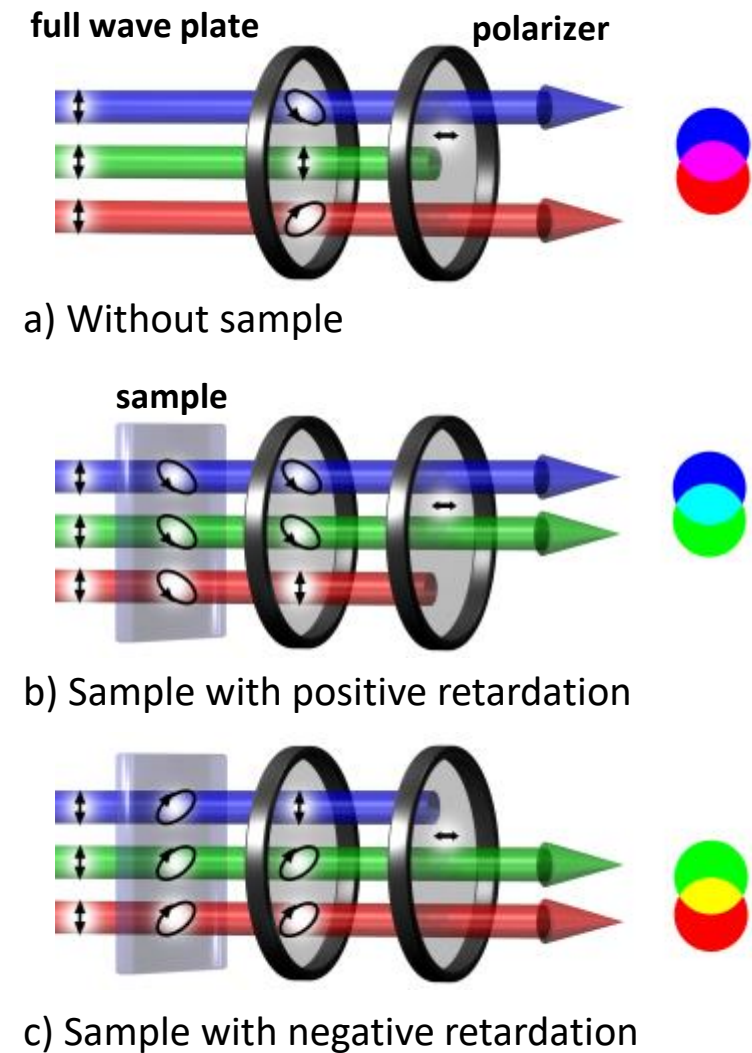
Full Wave Plate (1st Order Red Tint Plate)

- 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.

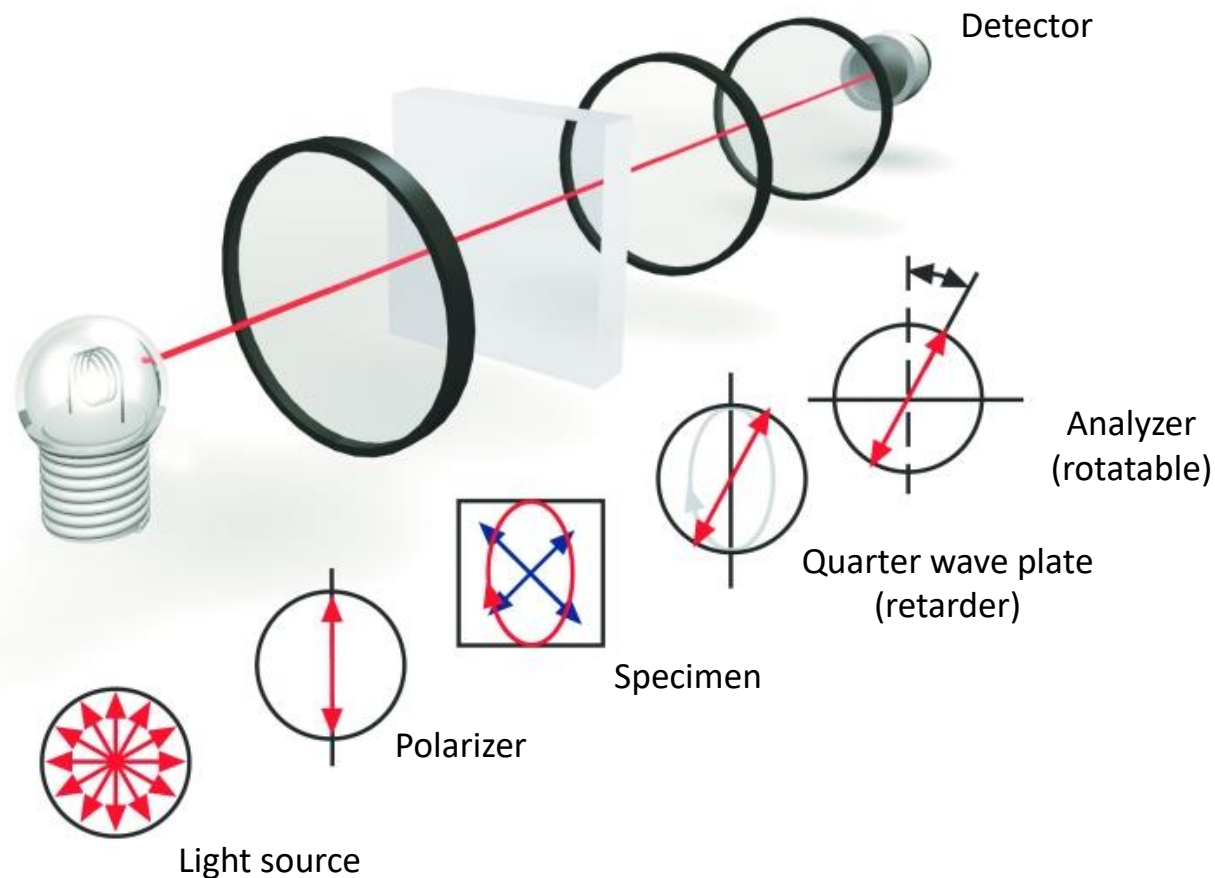


Full Wave Plate – Explanation

- a) Without a sample, the light does not change at 550 nm wavelength; However, light of other wavelengths is elliptically polarized and partially transmitted through 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



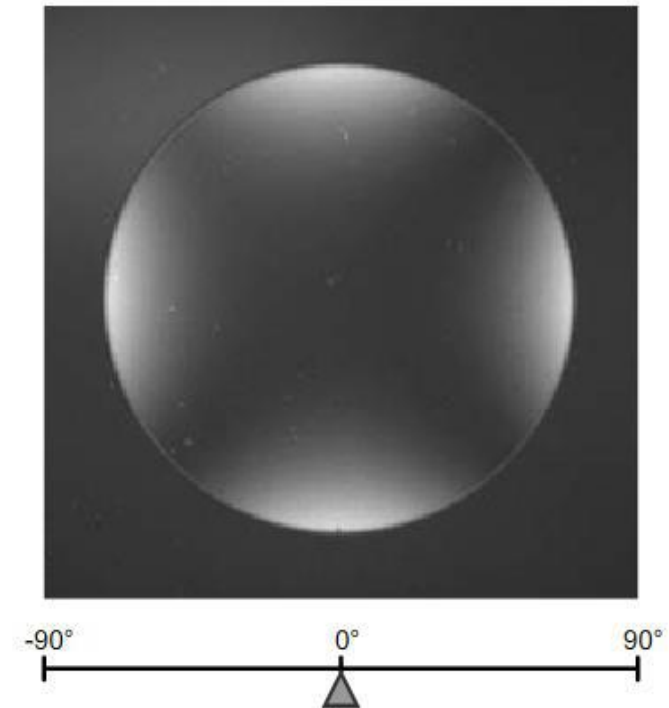
Polarimeter – Structure and Working Principle



- 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.

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.



Common Measurements Units

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

$$R = \alpha \cdot \lambda / 180^\circ \quad (\lambda = \text{used wavelength in nm})$$

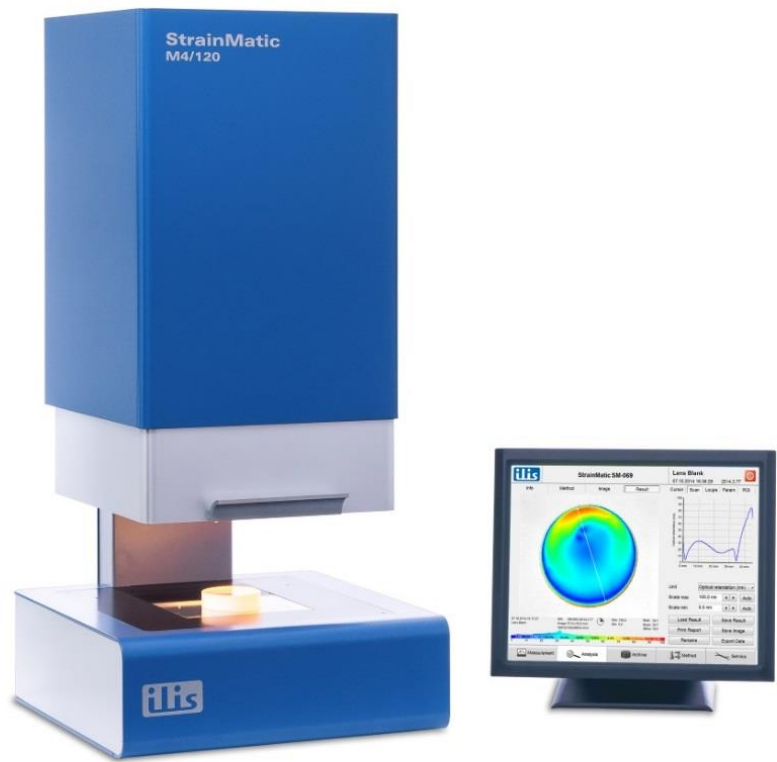
- If the birefringence along the measuring beam is homogeneous, the **normalized optical retardation** N in nm/cm can be calculated:

$$N = R \cdot (10 / d) \quad (d = \text{sample thickness in mm})$$

- 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:

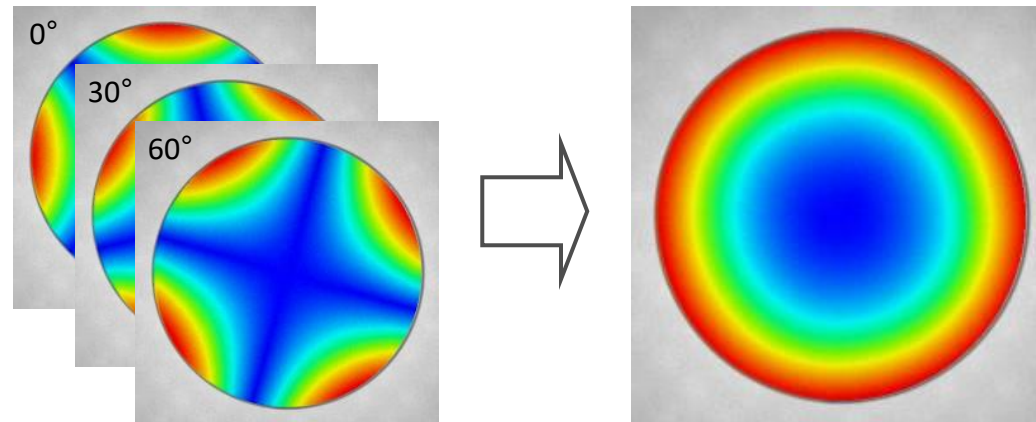
$$S = R / (d \cdot C) \quad (C = \text{photoelastic coefficient in TPa}^{-1})$$

Automatic Imaging Measurement



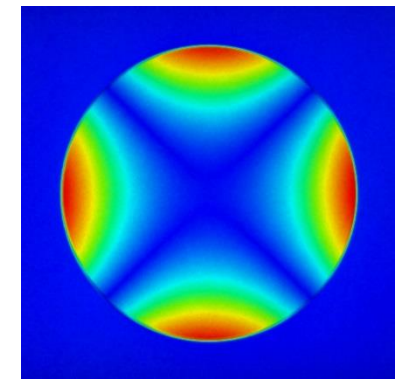
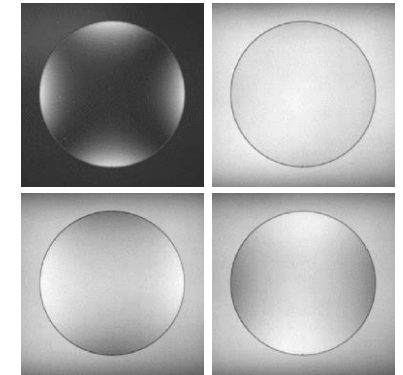
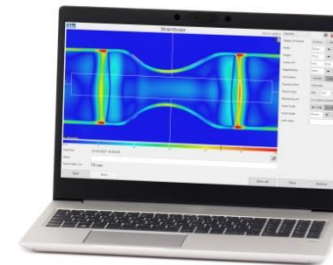
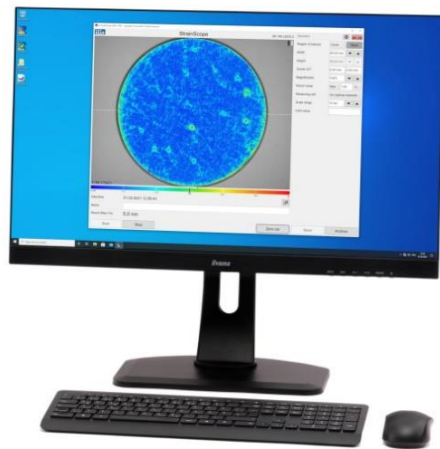
StrainMatic® imaging polarimeter system

- 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



Automatic Measurement in Real Time

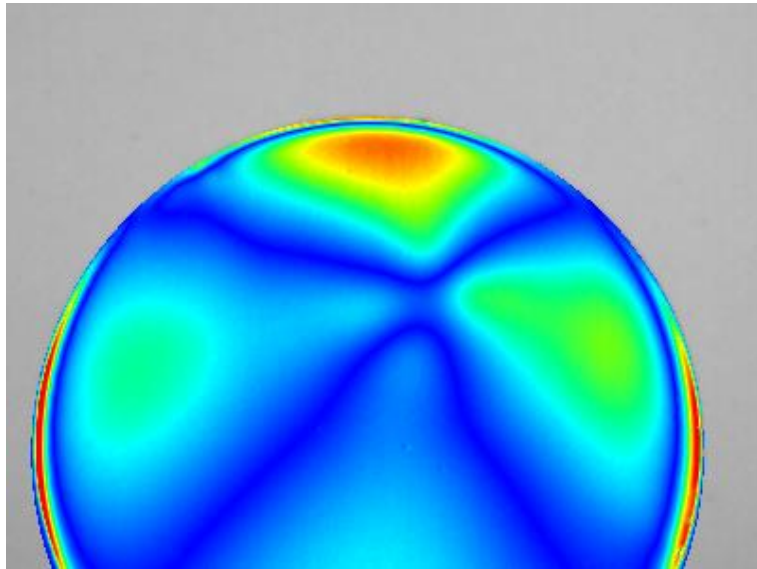
- Rotating analyzer replaced by a special polarization camera without moving elements
 - Measurement in real time (>20 Hz), also on moving objects and directly in the process



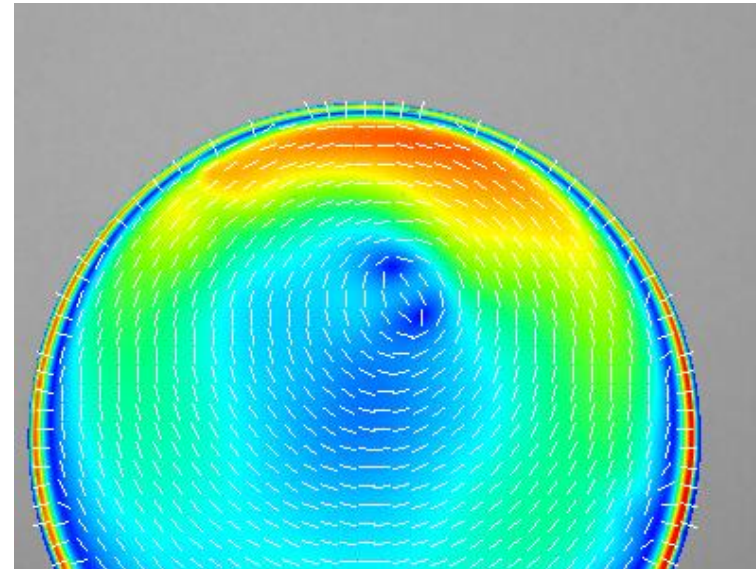
StrainScope® real time imaging polarimeters

Linear vs. Circular Polarization

- Measurement with circularly polarized light allows determination of correct magnitude and orientation of the stresses.



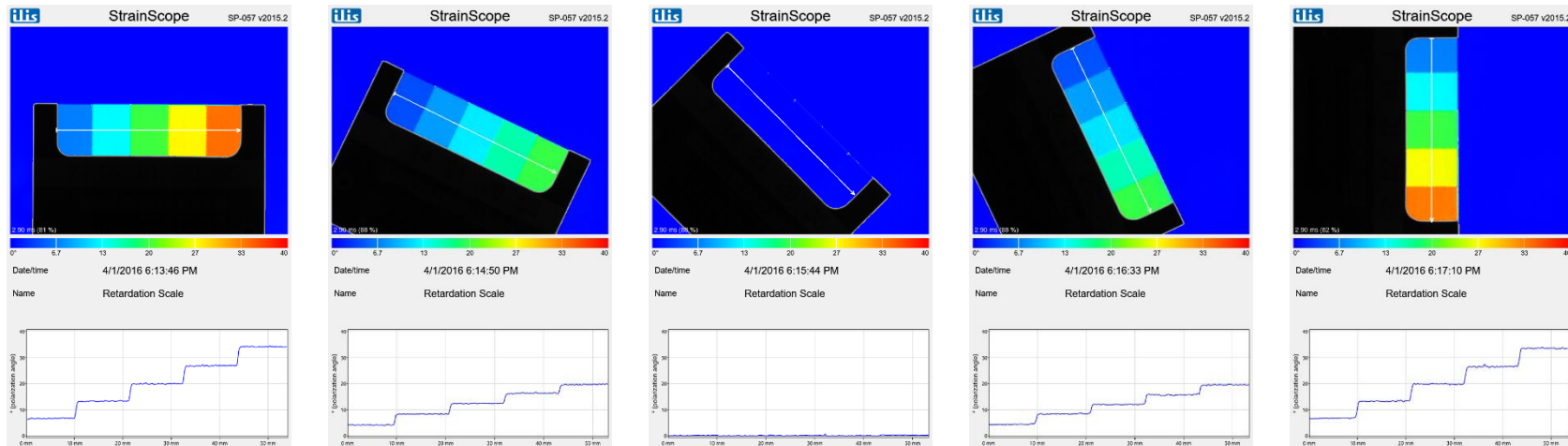
Linearly polarized light



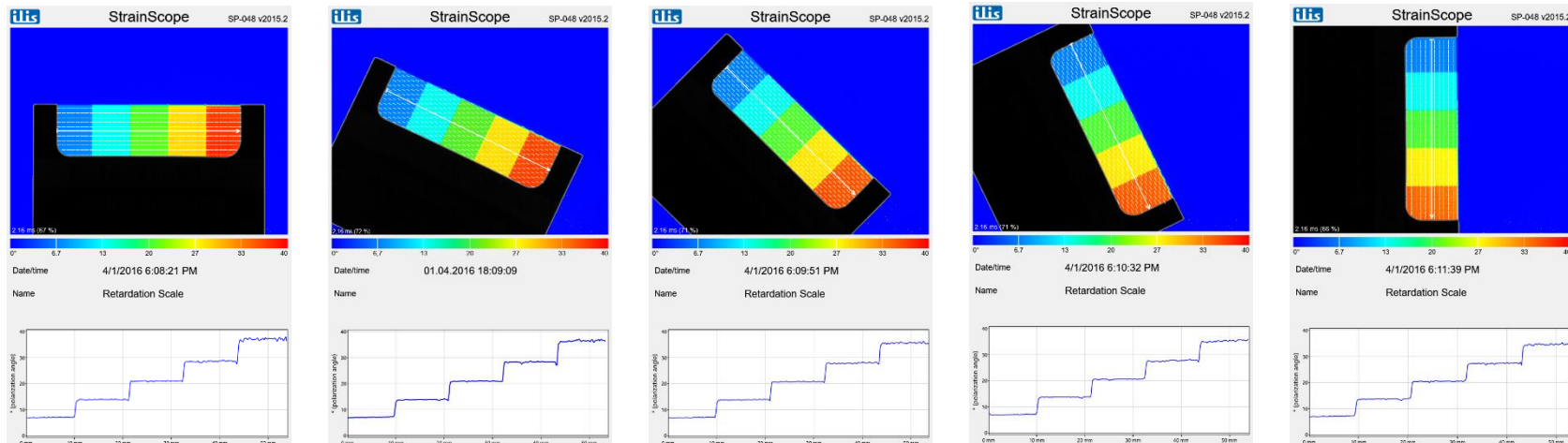
Circularly polarized light

Stress Orientation Dependency

Linearly
polarized
light

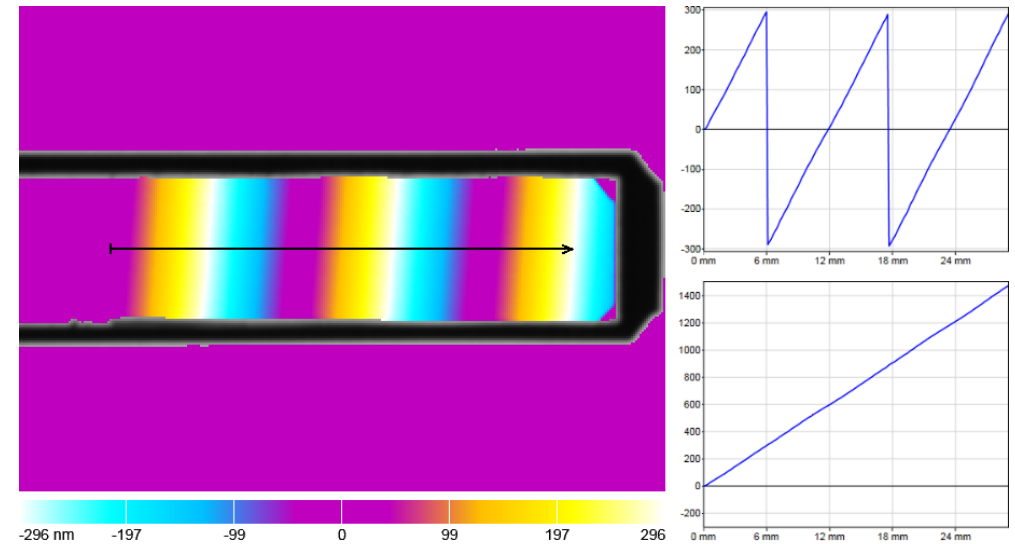


Circularly
polarized
light



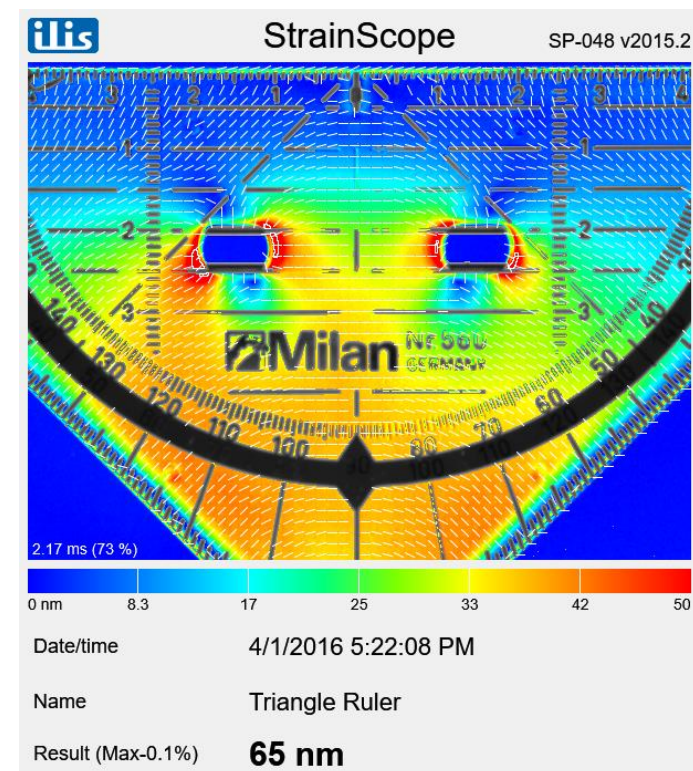
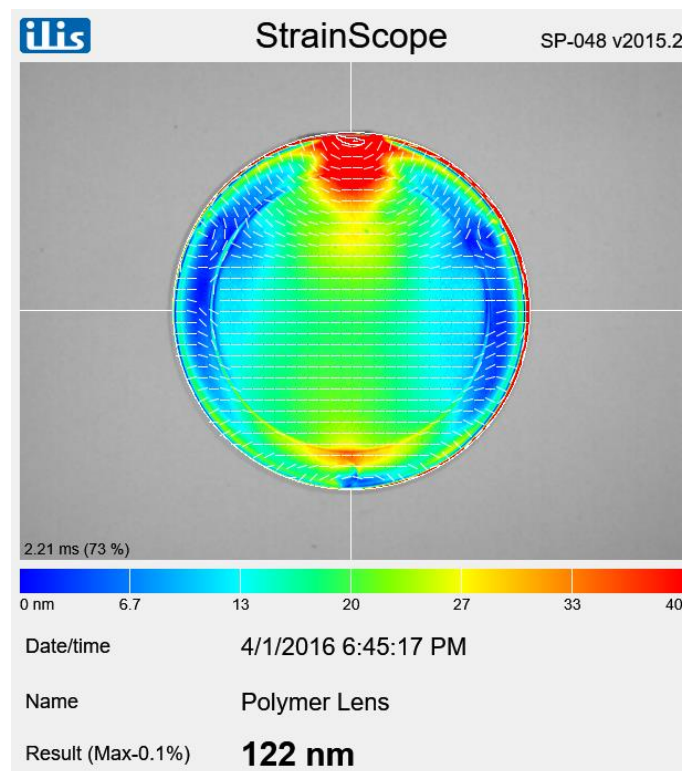
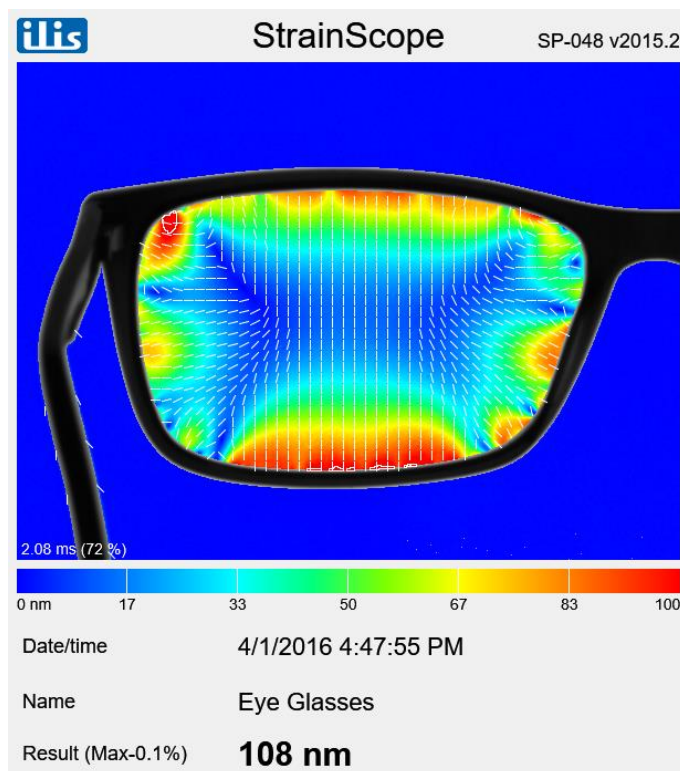
Measuring Range Limitations

- The applied Sénarmont principle limits the measuring range from $-\lambda/2$ to $+\lambda/2$ (first order).
- With circularly polarized light, the measuring range is even smaller (0 to $< \lambda/4$).
- This is not a problem for most glasses with small photoelastic coefficients ($\approx 2.6 \text{ TPa}^{-1}$), so that the results remain in the first order.
- However, it is an issue for many polymer materials showing much higher photoelastic coefficients, resulting in higher-order signals.

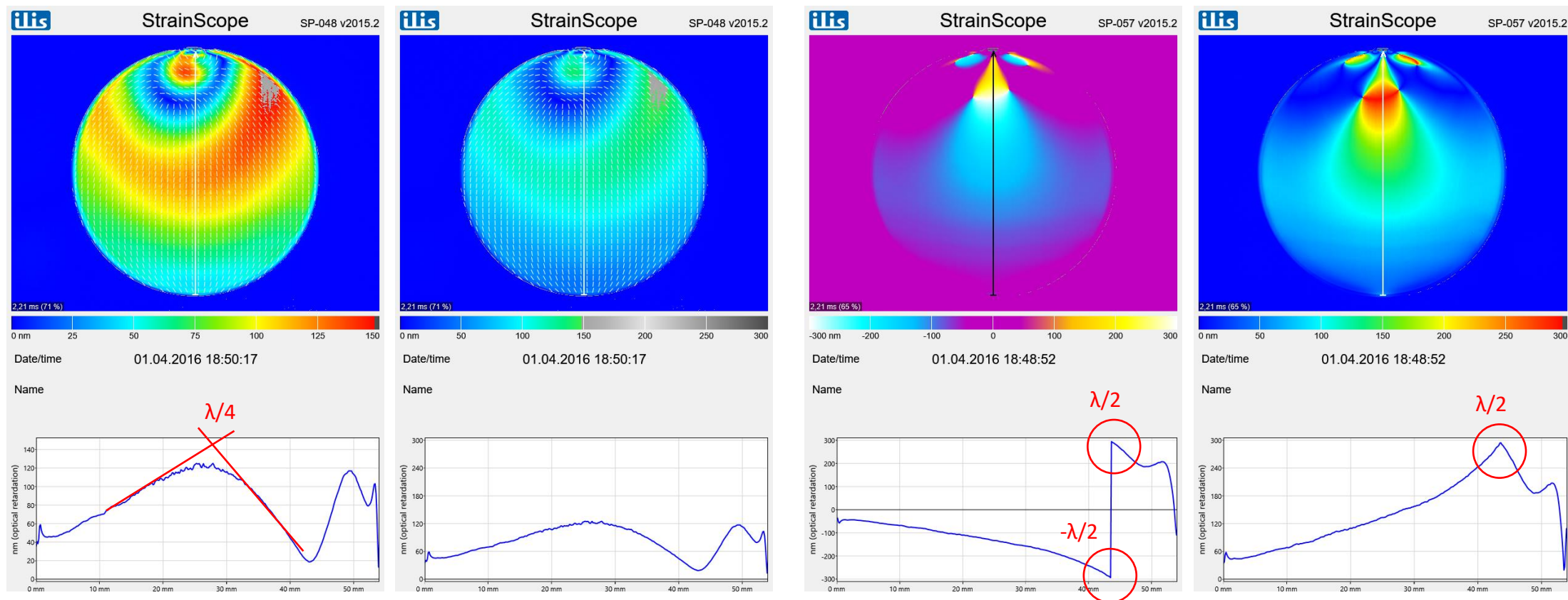


Measurement result of a quartz wedge. The diagrams show the optical retardation along the black arrow in the image (top: measured signal, bottom: true signal).

Measurement Examples (first order)



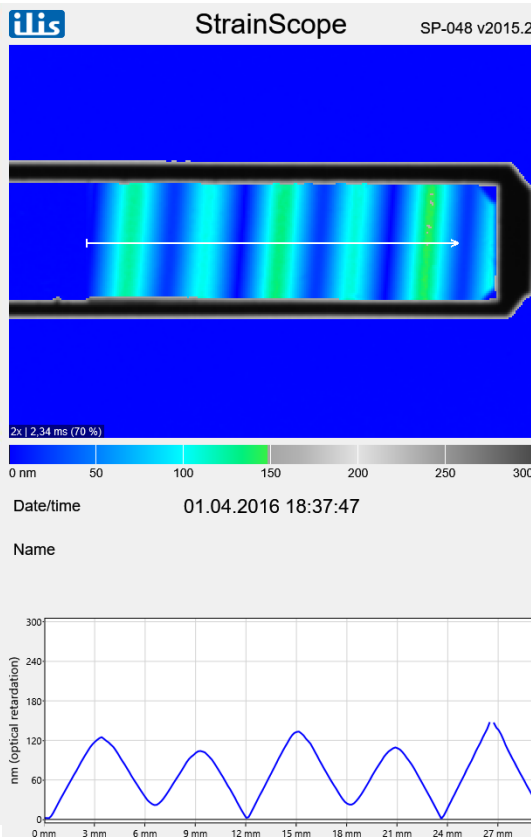
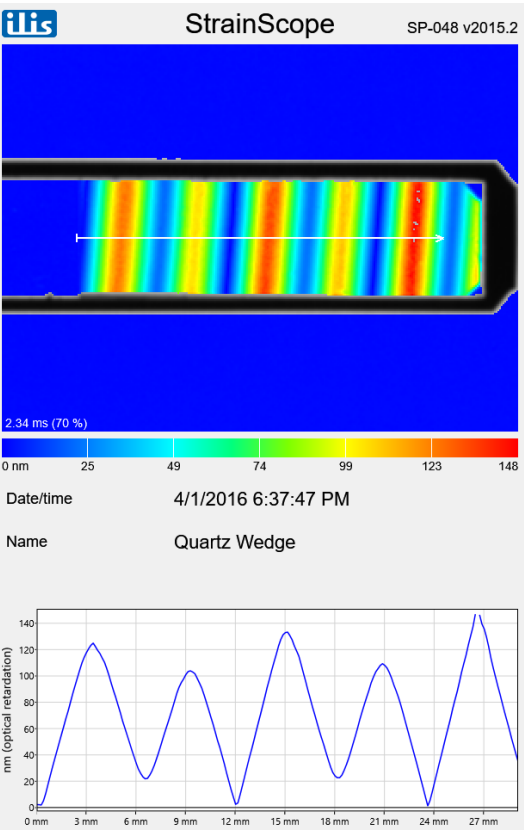
Measurement Example (second order)



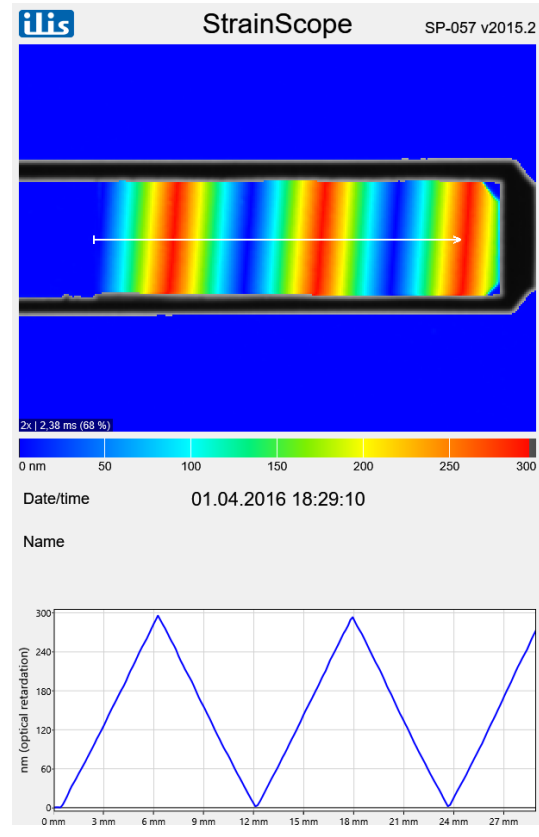
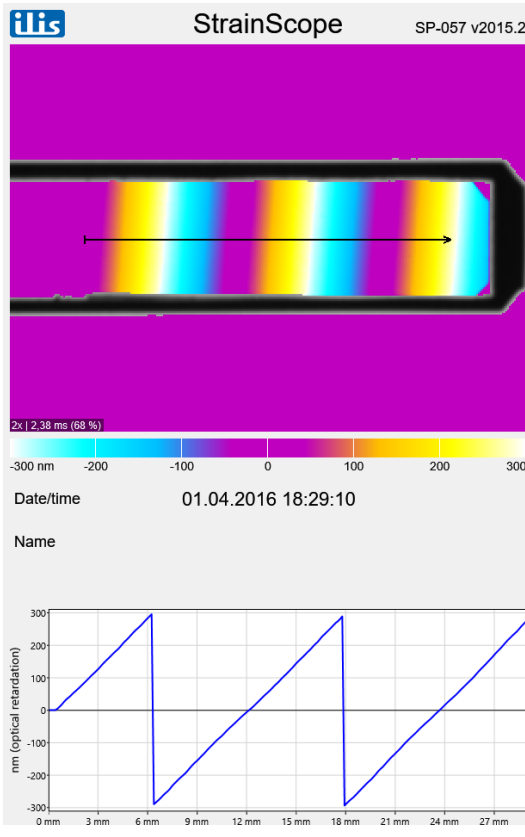
Circular polarization
($\lambda/4$ and $\lambda/2$ scale)

Linear polarization
(signed and absolute values)

Measurement Example (higher order)

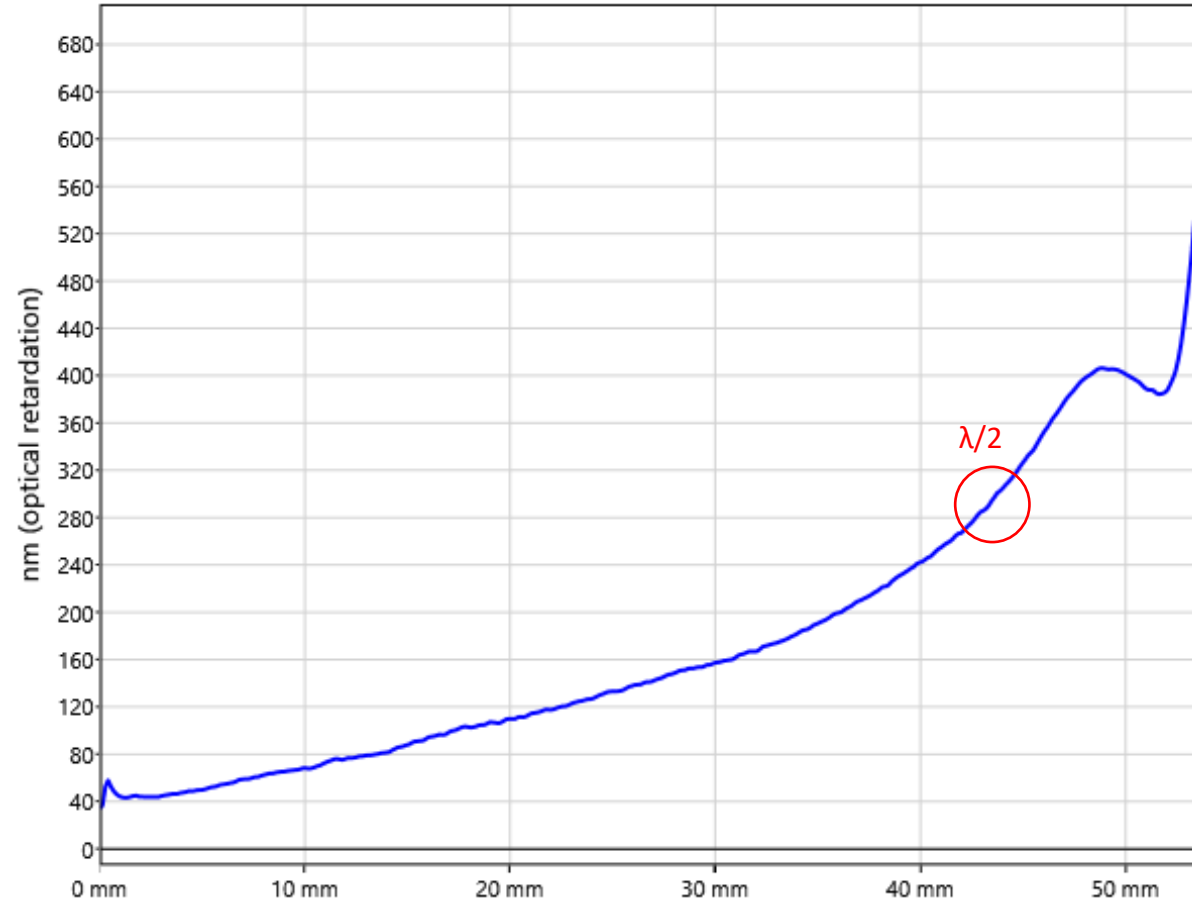
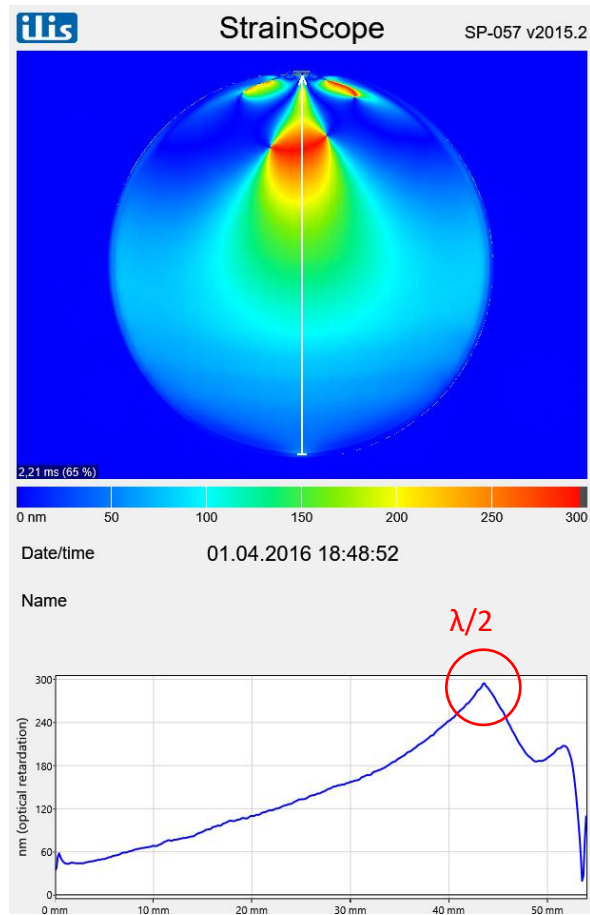


Circular polarization
($\lambda/4$ and $\lambda/2$ scale)



Linear polarization
(signed and absolute values)

Mathematical Correction



Summary and Conclusions

- Digital imaging polarimetry enables the objective measurement of residual stresses in transparent and optically isotropic materials.
- Using linear or circular polarization both have their advantages and disadvantages.
- The analysis of plastic materials such as polymer optics requires special care to avoid misinterpretations.
- Mathematical corrections or physical extensions (e.g. using several instead of just one wavelength) can help to analyze samples with high birefringence.

precision. nothing less.



Thank you for your attention!

Questions or comments?

