Stress Optics laboratory practice guide	2012

Transparent materials having internal mechanical stress are found to be birefringent, due to their *anisotropic* nature. That is, they demonstrate double refraction (having two indices of refraction) (Fig.1.) .Light polarized parallel to the director has a different index of refraction (that is to say it travels at a different velocity) than light polarized perpendicular to the director.

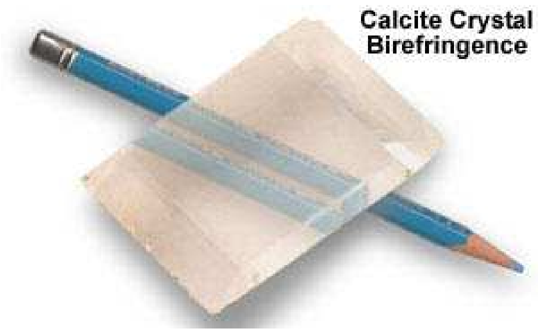


Fig.1. Double refraction = birefringence In Calcite Crystal

Thus, when light enters a birefringent material, the process is modeled in terms of the light being broken up into the fast (called the ordinary ray) and slow (called the extraordinary ray) components (Fig.2.) Because the two components travel at different velocities, the waves get out of phase. When the rays are recombined as they exit the birefringent material, the polarization state has changed because of this phase difference.

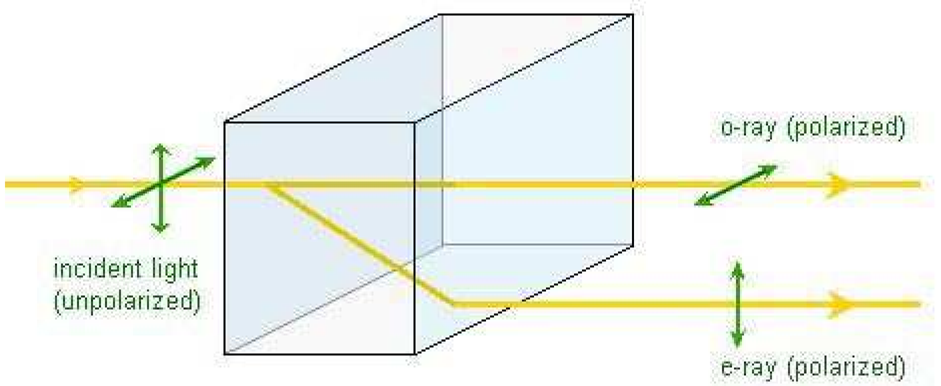


Fig.2. Light traveling through a birefringent medium will take one of two paths depending on its polarization. [4]

In order to understand the phenomenon: what is a polarized light; how to sum two polarized light rays with perpendicular plane polarization see Fig 3. The upper left corner of the picture shows light without polarization; the upper right corner of the picture shows linear polarized light. The lower pictures present how to sum two perpendicular plane polarized light with phase shift. If the shift between two polarized light equals $\lambda/4$: they will form circularly polarized light. If the shift between two polarized light not equals $\lambda/4$: they will form elliptically polarized light.

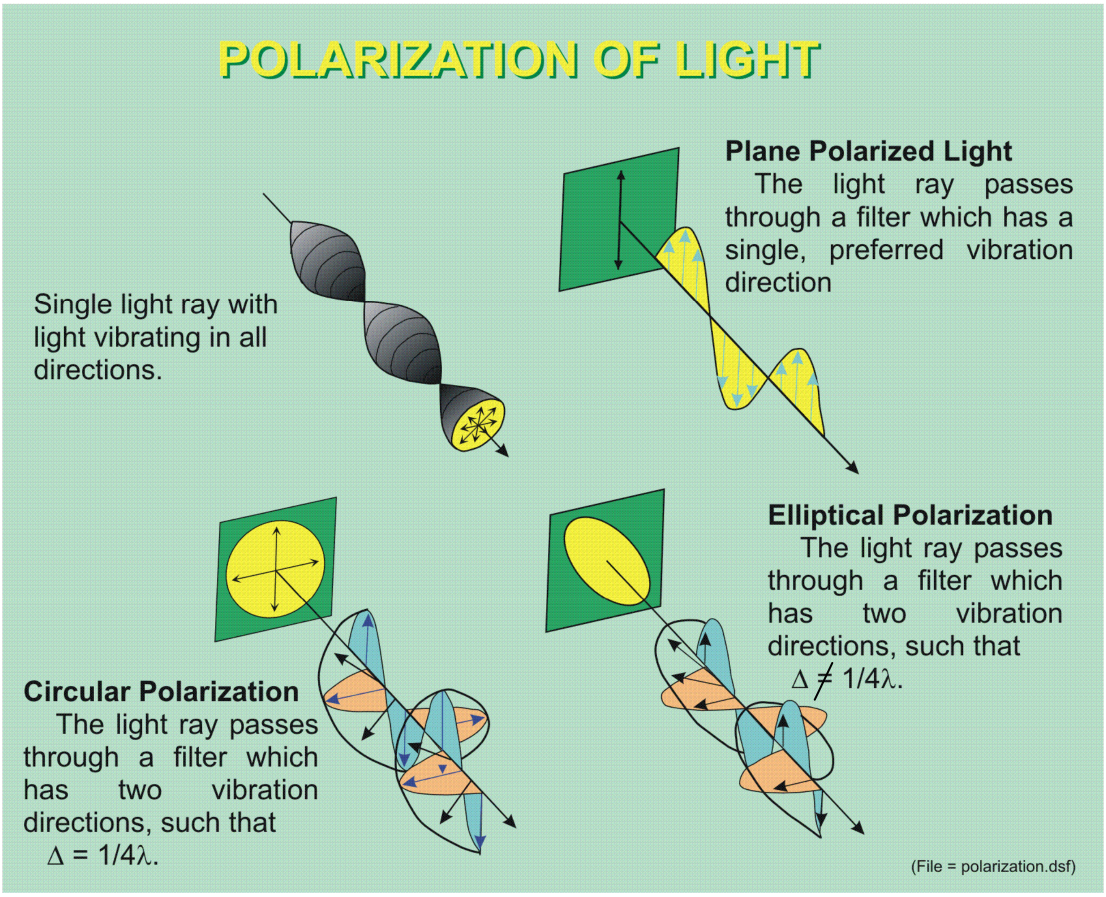


Fig 3 Polarized light and adding two perpendicular plane polarized light with phase shift

There are many methods producing polarized light: Polar filter, Nicol prism, reflection of light , where the incident angle equals the Brewster angle.

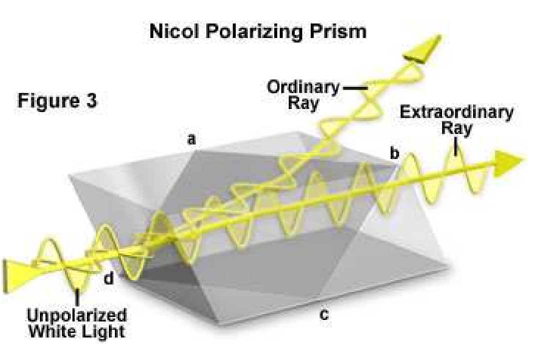
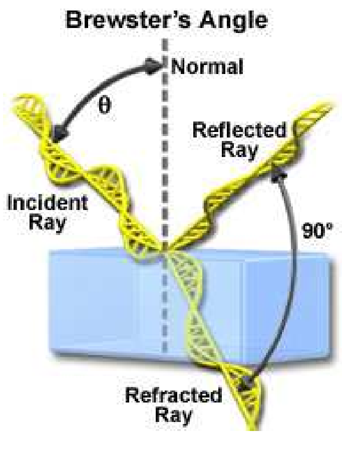
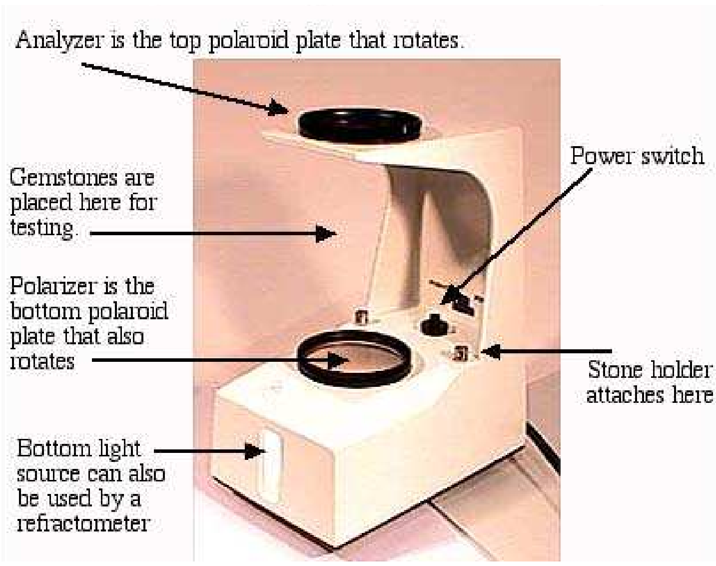
 	

Fig 4. Nicol prism producing polarized light	*Fig 5. Reflected light is polarized, where the incident angle equals the Brewster angle.*

When the beam arrives on the surface at a critical angle (Brewster's angle; represented by the variable **θ** in Figure 4), the polarization degree of the reflected beam is 100 percent, with the orientation of the electric vectors lying perpendicular to the plane of incidence and parallel to the reflecting surface. The refracted ray is oriented at a 90-degree angle from the reflected ray and is only partially polarized. For water (refractive index of 1.333), glass (refractive index of 1.515), and diamond (refractive index of 2.417), the critical (Brewster) angles are 53, 57, and 67.5 degrees, respectively.

Figure 5 is an illustration of the construction of a typical Nicol prism. A crystal of doubly refracting (birefringent) material, usually calcite, is cut along the plane labeled a-b-c-d and the two halves are then cemented together to reproduce the original crystal shape. A beam of non-polarized white light enters the crystal from the left and is split into two components that are polarized in mutually perpendicular directions.

Transparent materials having internal mechanical stress can be analyzed by a Polariscope. Polariscope (Fig 6.) has a light source, two linear polarizers set to perpendicular direction (Fig 7.), and has got a sample holder between the polarizers.



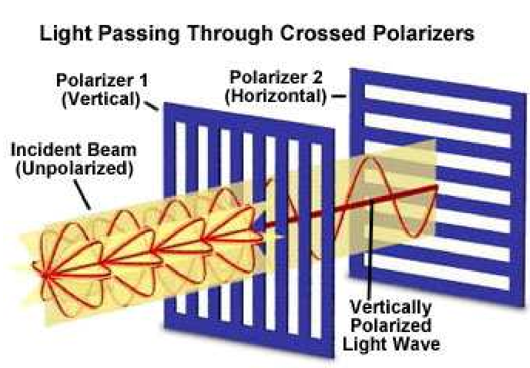


Fig 6. Polariscope *Fig 7. Arrangement of polarisers in polariscope*

If we place a birefringent material between the two perpendicular polarizers: in most cases elliptical polarized light will be formed (Fig 3), when this ray reaches the second polarizer, there is now a component that can pass through, and the region appears bright. Because of the birefringent nature of the sample, the incoming linearly polarized light becomes elliptically polarized.

Photoelasticity is an experimental method to determine the stress distribution in a material. The method is mostly used in cases where mathematical methods become quite cumbersome. The method serves as an important tool for determining the critical stress points in a material and is often used for determining stress concentration factors in irregular geometries.

The method is based on the property of birefringence, which is exhibited by certain transparent materials. Birefringence is a property by virtue of which a ray of light passing through a birefringent material experiences two refractive indices. The property of birefringence or double refraction is exhibited by many optical crystals. But photoelastic materials exhibit the property of birefringence only on the application of stress and the magnitude of the refractive indices at each point in the material is directly related to the state of stress at that point. Thus, the first task is to develop a model made out of such materials. The model has a similar geometry to that of the structure on which stress analysis is to be performed. This ensures that the state of the stress in the model is similar to the state of the stress in the structure.

When a ray of plane polarised light is passed through a photoelastic material, it gets resolved along the two principal stress directions and each of these components experiences different refractive indices. The difference in the refractive indices leads to a relative phase retardation between the two component waves. The magnitude of the relative retardation is given by the *stress optic law*:

$$R = Ct(\sigma_{11} - \sigma_{22}) \tag{1}$$

where R is the induced retardation, C is the stress optic coefficient, t is the specimen thickness, σ_{11} is the first principal stress, and σ_{22} is the second principal stress.

The two waves are then brought together in a polariscope. The phenomena of optical interference takes place and we get a fringe pattern, which depends on relative retardation. Thus studying the fringe pattern one can determine the state of stress at various points in the material (Fig. 9.)

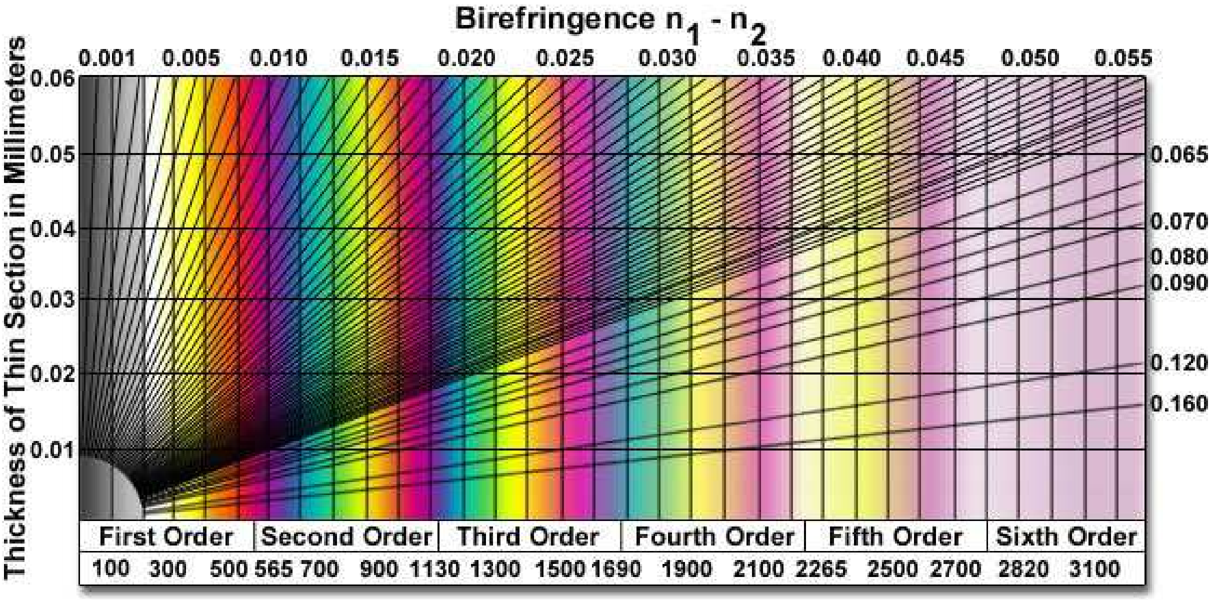


Fig 8. Michel-Levy interference color chart [1]

The birefringence of a anisotropic material can be estimated when observed and/or photographed in a Polariscope. A relationship between interference color and retardation can be graphically illustrated in the classical Michel-Levy interference color chart (Fig 8.), presented above. This graph plots retardation on the abscissa and specimen thickness on the ordinate. Birefringence is determined by a family of lines that emanate radially from the origin, each with a different measured value of birefringence corresponding to thickness and interference color. Table 1. shows interference colour-retardation assignment.

order	retardation (nm)	colour	order	retardation (nm)	colour
I	0	Black	**II**	845	greenyellow
	40	Dark grey		865	lightgreenyellow
	100	Lavender grey		910	yellow
	160	Greyish blue		950	orange
	220	grey		1000	bright orange
	235	Light green		1100	darkviolet
	260	white	**III**	1130	lightviolet
	270	Whiteyellow		1150	blueviolet
	275	LightgoldenYellow		1260	greenblue
	280	khaki		1335	darkseagreen
	305	Light Yellow		1375	brightgreen
	330	yellow		1425	greenyellow
	430	buff		1495	darkred
	505	orange		1535	orangered
	535	red		1620	orchid
	550	Deep red		1650	greymagenta
II	565	purple	**IV**	1680	greyblue
	575	royalblue		1710	darkseagreen
	590	mediumblue		1745	bluegreen
	665	Sky-blue		1810	lightgreen
	730	darkcyan		1930	palegreen
	750	green		2010	whitegrey
	825	lightgreen		2050	bright orange

Table 1. Interference colour-retardation assignment table

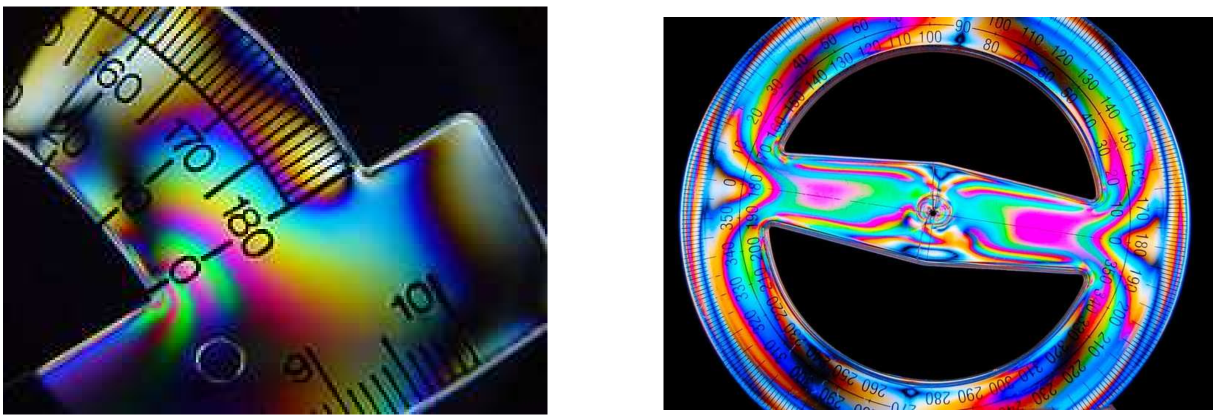


Fig. 9 Tension lines in plastic protractor seen under cross polarized light.

Applications of Polarized Light

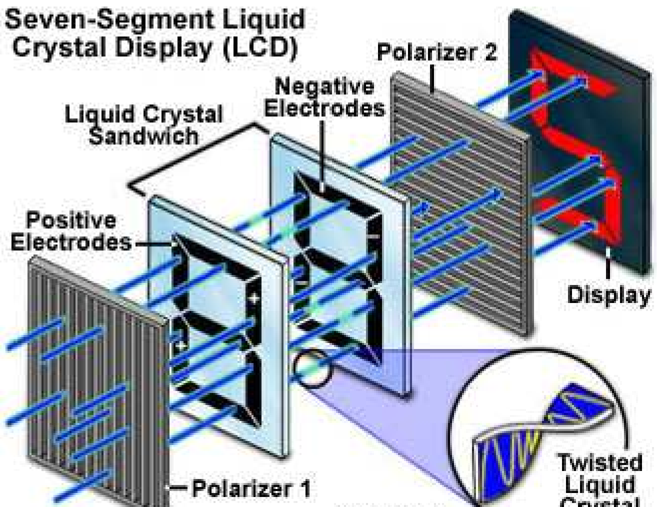


Figure 9

An excellent example of the basic application of liquid crystals to display devices can be found in the seven-segment liquid crystal numerical display (illustrated in Figure 9). Here, the liquid crystalline phase is sandwiched between two glass plates that have electrodes attached, similar to those depicted in the illustration. In Figure 9, the glass plates are configured with seven black electrodes that can be individually charged (these electrodes are transparent to light in real devices). Light passing through polarizer 1 is polarized in the vertical direction and, when no current is applied to the electrodes, the liquid crystalline phase induces a 90 degree "twist" of the light that enables it to pass through polarizer 2, which is polarized horizontally and is oriented perpendicular to polarizer 1. This light can then form one of the seven segments on the display.

When current is applied to the electrodes, the liquid crystalline phase aligns with the current and loses the cholesteric spiral pattern. Light passing through a charged electrode is not twisted and is blocked by polarizer 2. By coordinating the voltage on the seven positive and negative electrodes, the display is capable of rendering the numbers 0 through 9. In this example the upper right and lower left electrodes are charged and block light passing through them, allowing formation of the number "2" by the display device (seen reversed in the figure).

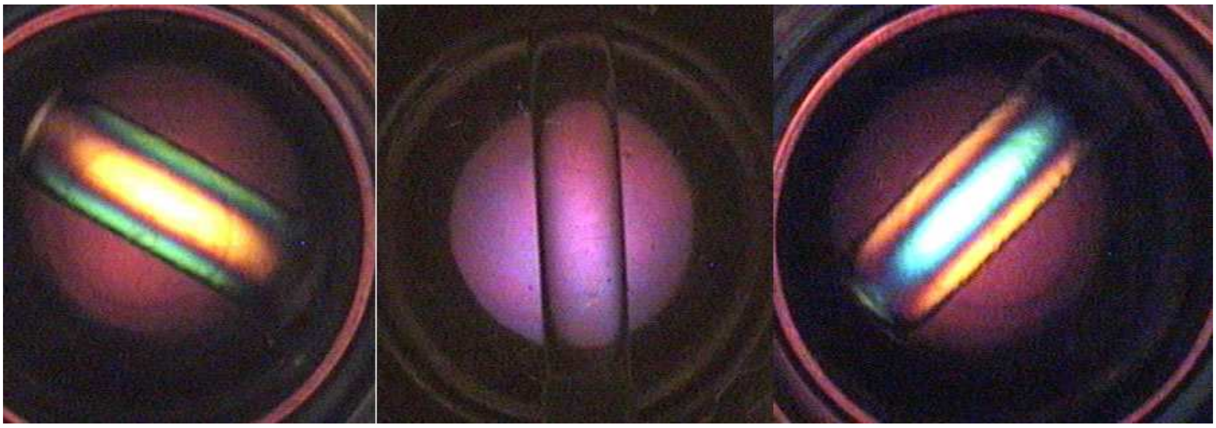
Measurement tasks:

In case of a Polariscope examination of transparent samples we have to ask two questions:

- How the sample made: what kind of stress distribution we assume?
- How the perpendicular polar filter pair influence the interference colour?

1. Polariscope direction calibration

The interference colour will depends on the angle we place the sample into the Polariscope, So we have to make a directional calibration using a suddenly cooled glass rod: the outer layer has got compressive stress, the internal cone is in tensile state.



-45^o maximal colour contrast . Compressive stresses enlarge the retardation Fig. 10.	0^o The direction of the rod equals the direction of a polarizer: we can not see the colours.	$+45^o$ Compressive stresses lower the retardation

2. Paring colour with retardation of staged cellophane tape layers.

3. Calculation glass sample stress

If we have only one axle stress, the above mentioned equation (1) will be:.

$$\boldsymbol{R = C\, t\, \sigma} \qquad (2)$$

Where:

***σ*:**	stress	(N/mm^2)
***R*:**	retardation	(nm)
***t*:**	sample thickness	(mm)
***C*:**	stress optic coefficient	$\frac{nm/mm}{MPa}$

C value:	
Tender glass	2,5
Lead-glass	3
Hard glass	4

The stress optic coefficient for glass is a small value, which causes small retardation. In this case use the quarter wave plate causing plus 550 nm retardation; it will transform the interference colors into bright region of Michael-Levy scale.

4. Calculation of stress optic coefficient

Calculation of stress optic coefficient from measurement data with the aid of overhead projector Polariscope and force gauge. Pull the sample with 10, 20, 30 N force. Calculate the tensile stress from the equation:

$$\sigma = \frac{F}{A} \tag{3}$$

Were

σ is the tensile stress N/mm^2

F is the load force in N

A is the cross section of the sample in mm^2

Allocate the retardation using Table 1.

Calculate the stress optic coefficient from equation (2)

5. Stress analysis of glass and plastic samples

Control Questions

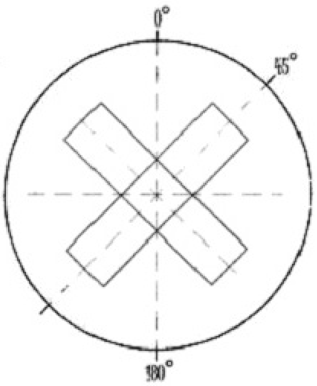
What is birefringence?
Define linear polarized light!
Define circular polarized light!
Describe the Parts of a Polariscope and its arrangement!
Internal stress calculation of transparent material

Literature

[1] http://micro.magnet.fsu.edu/
[2] http://www.microscopyu.com
[3] Gröller György: Feszültségoptika laboratóriumi útmutató
[4] http://plc.cwru.edu/tutorial/enhanced/files/lc/biref/biref.htm
[5] http://micro.magnet.fsu.edu/primer/java/polarizedlight/michellevy/index.html
Interactive Michael-Levy Chart JAVA tutorial

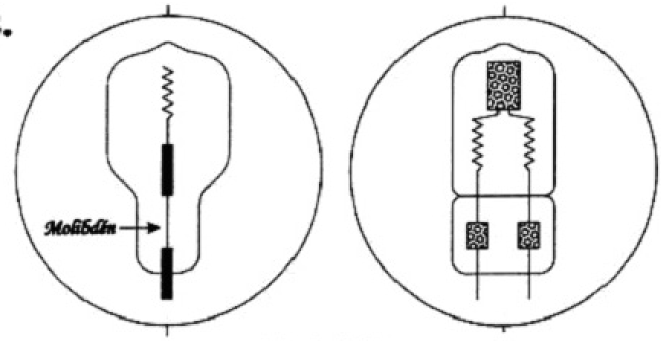
Report of the Stress Optics laboratory practice	*Made by:* ……………………………………………… ……… *Name neptun code, group identification*	
Leader of laboratory practice:	*Date:*	*Note:*

1.



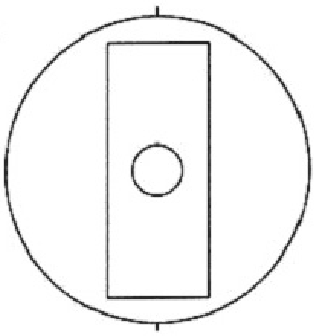
Two base positions of a glass rod

2.



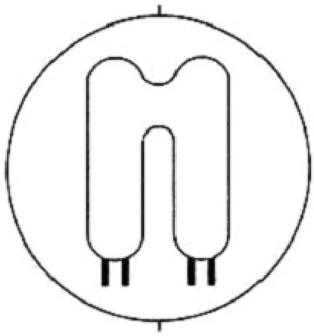
Glass to metal seal in halogen lamp: Molybdenum and fused silica (or hard glass in the recent lamps)

3.



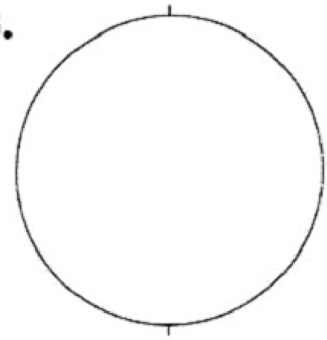
Plexiglass modell to show mechanical stress

4.



Compact fluorescent lamp

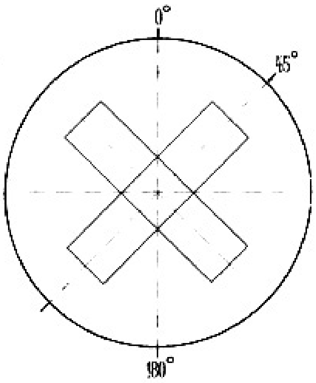
5.



Your favourite picture

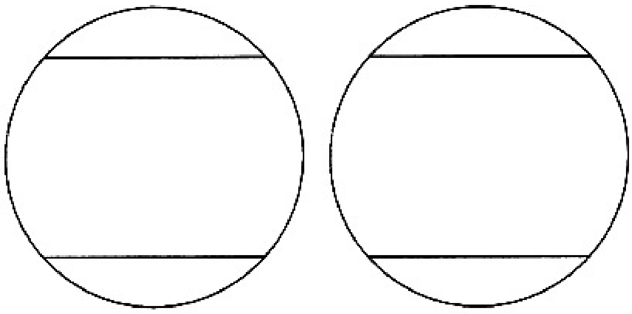
Report of the Stress Optics laboratory practice	*Made by:* ……………………………………………. ……… *Name neptun code, group identification*	
Leader of laboratory practice:	*Date:*	*Note:*

1.



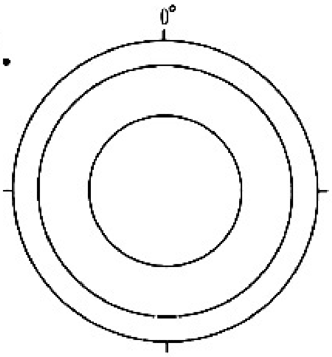
Two base positions of a glass rod

2.



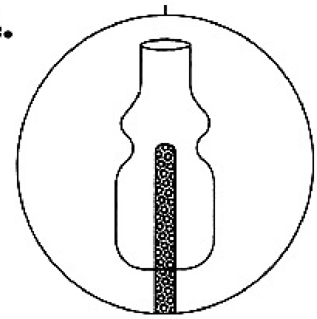
Tempered and annealed glass sample. Tha same glass in two positions or two different glasses. Mark the main directions of the polarograph!

3.



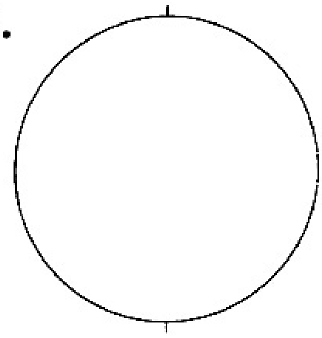
Plexiglass ring. Press it with your fingers and mark the direction of pressing!

4.



Glass to metal seal in xenon lamp: Tungsten and fused silica

5.



Your favourite picture

Retardation assignment of cellophane tape layers

Number of layers	Color name	Coloration	Retardation (delay) in nm

Determination of stress optical coefficient of polyester sample

cross section data:	thickness: d = mm	width: a = mm	cross section: mm^2

F_0 = 0 N		R_0 =	
F_1 = 10 N	σ_1 =	R_1 =	c =
F_2 = 20 N	σ_2 =	R_2 =	c =
F_3 = 30 N	σ_3=	R_3 =	c =
			C_{mean} =