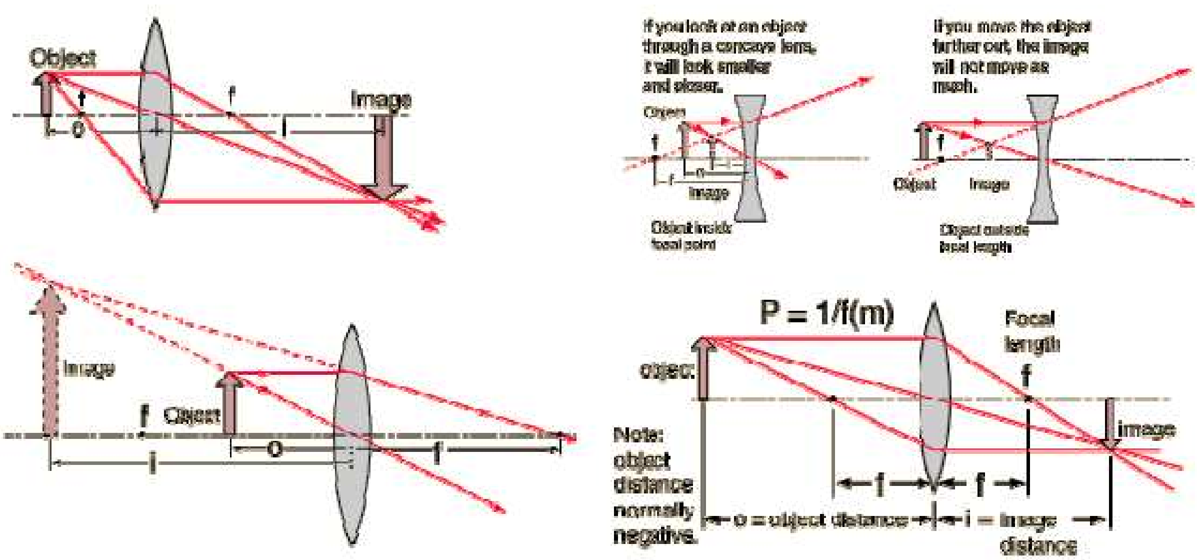
Optics measruments

To recall the studies of the most frequent and basic optical devices, it is recommended to look at the following figures.



1. Fig. Mapping of basic optical devices

Determining the focal length of a lens:

The focal length of a converging lens can be determined by the following two methods:

- By the thin lens formula, i.e. measuring the image distance of the projection of az object, placed out of the focal length.
- Bessel-method: Fixing the position of the object and the image (their distance is *s*), there are two places of the lens, when the image is perfect. If the distance of these places is *d*, the focal length:

$$f = \frac{(s-d)(s+d)}{4s}$$

Determining the refractive index by reflection.

The light (as an electromagnetic radiaton) partially reflected, partially transmitted and partially absorbed in a material. The proportion of these three contribution depends on the material and the wavelength of light.

The reflected and transmitted part can be measured easily and the absorbed contribution can be determined by the energy-consevation law.

As the electromagnetic radiation is tranversally polarized wave, it is necessary to examine the polarization dependence of the reflection. It follows that one should use linearly polarized light.

Lets take a linearly polarized light, and the border of two media, with different refractive index. For simplicity we assume that the first material (incoming and reflected rays) is air (n=1) and, we neglect the absorption. The intensity of the incoming, reflected and transmitted ligth is noted by I_o, I_R and I_T respectively.

In the case of perpendicular incidence the the reflected and transmitted rays are perpendicular to the border too. Due to the energy-consevation law:

$$I_o = I_R + I_T$$

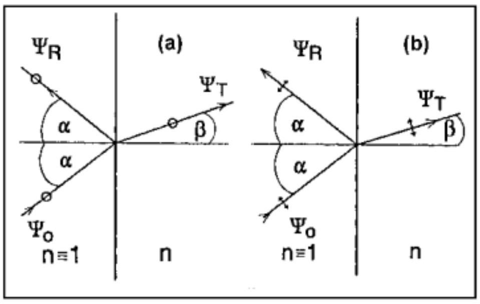
Expressing the intesity of the reflected and transmitted ray with the intensity of the incoming ray and the refractive index:

$$I_R = \left(\frac{n-1}{n+1}\right)^2 I_o$$

$$I_T = \frac{4n}{(n+1)^2} I_o$$

Even in the case of perpendicular incidence a not negligable portion the light is relfected (e.g. for glass (n=1.5) 4% of the incident light is reflected).

If the incident, linearly polarized wave is not perpendicular to the border the media, two cases should be examined: (a) when the polarization is perpendicular to the plane of incidence, (b) when the polarization lies within the plane of incidence. Reminder: the plane of incidence is the plane defined by the incident, reflected and transmitted rays. These two cases are show on Fig.2, where the direction of polarization is noted by circle and bi-directional arrow.



2. Fig.

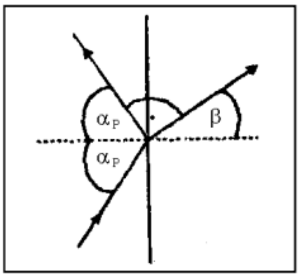
The proportion of the amplitude of different rays are given by the so called Fresnel-formulae. Without details of the derivation the formulae for case (a):

$$\frac{\Psi_{T\perp}}{\Psi_{o\perp}} = \frac{2}{1 + n\dfrac{\cos\beta}{\cos\alpha}}, \qquad \frac{\Psi_{R\perp}}{\Psi_{o\perp}} = \frac{-1 + n\dfrac{\cos\beta}{\cos\alpha}}{1 + n\dfrac{\cos\beta}{\cos\alpha}}$$

where ⊥ notes the components perpendicular to the plane. For case (b):

$$\frac{\Psi_{T\parallel}}{\Psi_{o\parallel}} = \frac{2}{n + \dfrac{\cos\beta}{\cos\alpha}}, \qquad \frac{\Psi_{R\parallel}}{\Psi_{o\parallel}} = \frac{n - \dfrac{\cos\beta}{\cos\alpha}}{n + \dfrac{\cos\beta}{\cos\alpha}}$$

where ∥ notes the components parallel to the plane.



3. Fig.

The reflected (transmissitted) amplitude of a wave with arbitrary angle of incidence and polarization direction can be calculated with Fresnel-formulae. Squaring the amplitudes, the intensies can be determined. Also the polarization of the reflected (transmitted) rays can be determined. To demonstrate this, lets take the Brewster's Law, which states that at certain angle of incidence (α_p) the reflected and transmitted beams are perpendicular ot each other, and the reflected beam is totally linearly polarized. With notation of Fig.3 $\beta = 90° - \alpha_p$ and due to Snell's Law

$$\frac{\sin \alpha_p}{\sin \beta} = \frac{\sin \alpha_p}{sin(90° - \alpha_P)} = \frac{\sin \alpha_p}{\cos \alpha_p}$$

so

$$\tan \alpha_p = n$$

This is called Brester's Law. Examine the Fresnel-formulae in case of $\alpha = \alpha_p$. If the polarization is parellel to the plane of incidence, than

$$\frac{\cos \beta}{\cos \alpha_p} = \tan \alpha_p = n$$

so

$$\Psi_{R\parallel} = 0$$

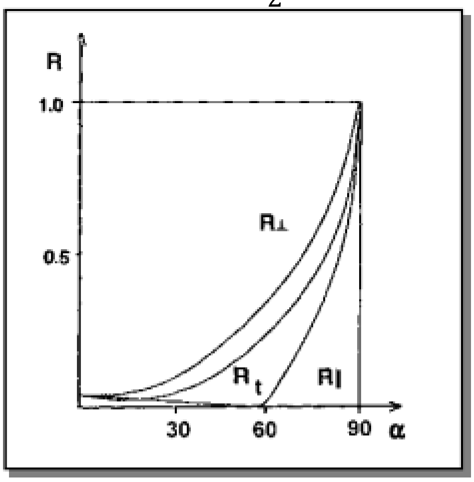
so the intensity of the reflected wave is zero.

In the case of perpendicular polarization a finite contribution canbe transmitted to second medium

$$\Psi_{T\perp} = \frac{2}{1 + n^2} \Psi_{o\perp} \neq 0$$

To demonstrate the formulae above, Fig.4 shows the relfectivity, $R = (\Psi_R/\Psi_o)^2$ as a function of angle of incidence for glass, with refractive index n=1.5. On the figure $R_\parallel$ corresponds to the light polarized parallel with the plane of incidence, $R_\perp$ corresponds to the perpendicularly polarized case, and R_T for the natural light

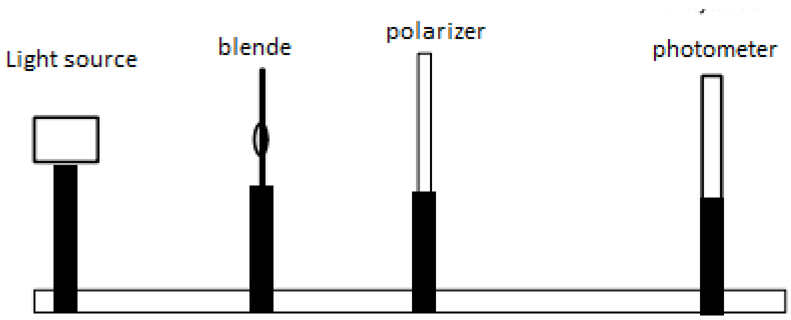
$$R_T = \frac{R_\parallel + R_\perp}{2}$$



4. Fig.

Studying the polarization of light sources

The polarization of a common tungsten lamp and a laser diode is examined.



5. Fig.

Determining a micron scale displacement by interferometer

Since a light beam can be modelled as oscillating electric and magnetic field, when two or more beams meet the electric and magnetic fields are added due to the superposition principle. That is in every point of the space the electric and magnetic field is the vectorial sum of fields of each beam.

If the beams originate from different sources, generally there is no connection between the electromagnetic oscillations. In every moment there are points is space where adding the fields results in maximum and points where results in cancellation. Since there is no definite connection, where a maximum was at a given moment, in the next moment there can be a minimum. The frequency of the visible light is too high for the human eye, it will average out the fast oscillation of the intensity.

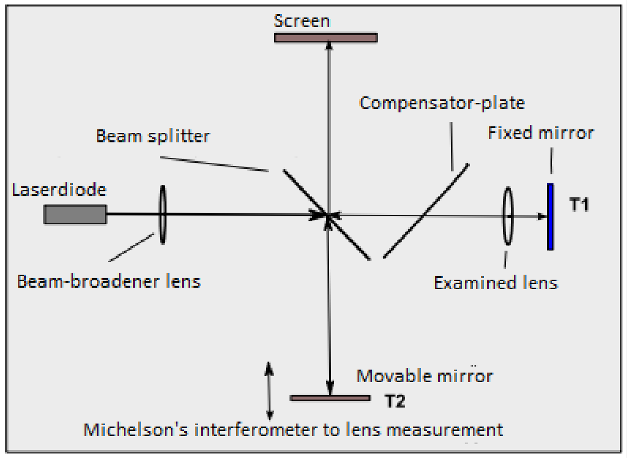
If the beams originate from the same source, there is a correlation between the the phase of the oscillations, so points can exist, where the beams are in phase continously. In this case the total fields are always maximal in these points, and bright spot is visible there. In the points where the beams are always in opposite phase, the total intensity is minimal, a dark spot is visible.

First Thomas Young made interference pattern with two closely placed slits. The resulting image consisted bright and dark stripes. This experiment was an important proof of the wave nature of light.

The slits can be used as simple interferometer. In the distance between the slits is known, the wavelength of the light can be determined by measuring the distance of the maxima and minima. If the wavelength is known, the distance of the slits can be determined.

Michelson's interferometer

In 1881, 78 years after Young, A. A. Michelson built a similarily working interferometer. Michelson's original intention was to prove the existance of ether – the hypothetical medium which was hold for responsible for the propagation of electromagnetic radiation (such as light). Partially his work proves that this hypothesis was wrong. Furthermore Michelson's interferometer is widely used to measure the wavelenght of light, or if it is known, to measure very small displacement.



6. Fig.

On Fig.6 the sketch of Michelson's interferometer is shown. The beam of laser is split by a beam splitter, which reflects the 50% of the intensity and transmits the other 50%. One the split beams is reflected on a fixed, the other is relfected on a movable mirror. Both beams return to the beam splitter. Now the half of light reflected from the movable mirror goes to the screen, also the half of the other beam goes to the screen.

This way the original beam is split to two different paths and a part of them merge again. Since the beams originate from the same source, their phase are strongly correlated. If a lens is used between the laser and the beam splitter, the beams are broadend and an interference pattern consisting of bright and dark rings is visible on the screen (Fig.7).

7. Fig.

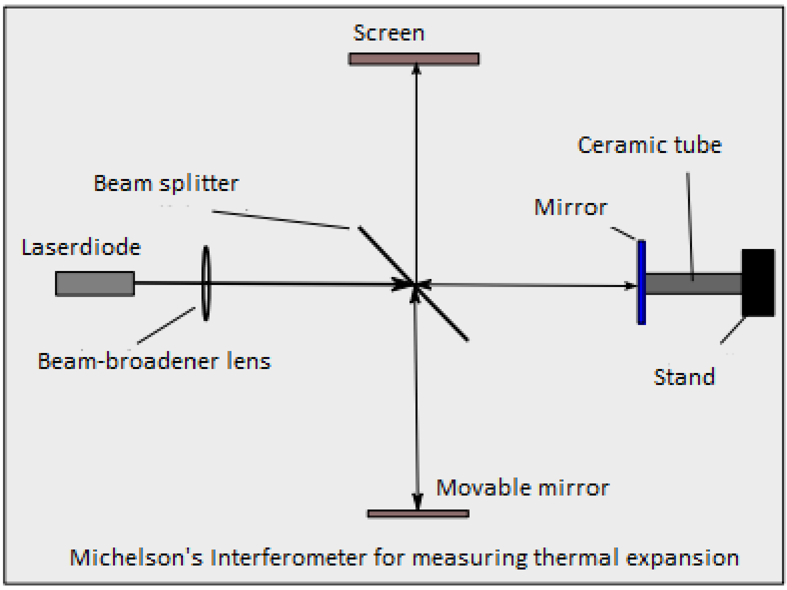
Since the two interfering beams of light were split from the same initial beam, they were initially in phase. Their relative phase, when they meet at any point on the screen, depends on the difference in the length of their optical paths before reaching that point.

By moving mirror T_2, the path length of one of the beams can be varied. Since the beam traverses the path between T_2 and the beam-splitter twice, moving T_2 1/4 wavelength nearer the beam-splitter will reduce the optical path of that beam by 1/2 wavelength. The interference pattern will change; the radii of the maxima will be reduced so they now occupy the position of the former minima. If T_2 is moved an additional 1/4 wavelength closer to the beam-splitter, the radii of the maxima will again be reduced so maxima and minima trade positions. However, this new arrangement will be indistinguishable from the original pattern.

By slowly moving T_2 a measured distance $\mathbf{d_N}$, and counting **N**, the number of times the fringe pattern is restored to its original state, the wavelength of the light (λ) can be calculated as:

$$\lambda = \frac{2d_N}{N}$$

If the wavelength of the light is known, the same procedure can be used to measure $\mathbf{d_N}$.



8. Fig. Determining the thermal expansion coefficient:

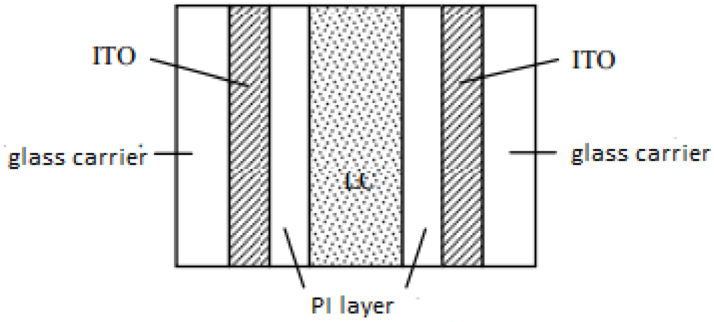
From Fig.6 it is evident, that one of the beams crosses the beam splitter only once, while the other three-times. If the light source is strongly coherent and monochromatic, such as a laser, it is not a problem. Although in case of other light sources it can result in error. As the length of optical path increases, the coherence of split beams is decreasing, which can distort the interference pattern.

Using a compensator plate (see Fig.6) both beams crosses glass object three-times, which solves this problem. The compensator plate is similar as the beamsplitter, but without reflecting coating.

With Michelson's interferometer one can examine optical devices. E.g. placing a lens, as only one of the split beams crosses it, every small deviation of the lens will result in strong distortion of the interference pattern.

Liquid crytals:

The liquid crystal (LC) is such a state of matter, which is between the crystallic solid state and the liquid state. The nematic LC-s are organic compounds, which consist of long, needle-like molecules. The orientation of the molecules can easily be ordered and changed, by the means of electric field. For LC devices one needs to orient the molecules to the (closely) same direction. The structure of the LC cell used for the meaurement is shown on Fig.9. The glass carrier-plates are coated with electrically conducting, but optically transparent indium-tin-oxide (ITO), and a thin polyimid (PI) ordering layer is formed on this. The PI layer is polished to form microscopic trenches. These trenches order the LC molecules which are placed between two carrier-plates. With this polishing method the LC mocelules are well-oriented and due to the forces acting between the molecules the whole LC-prism is oriented to the same direction. The direction of the molecules called the „director".



9. Fig.

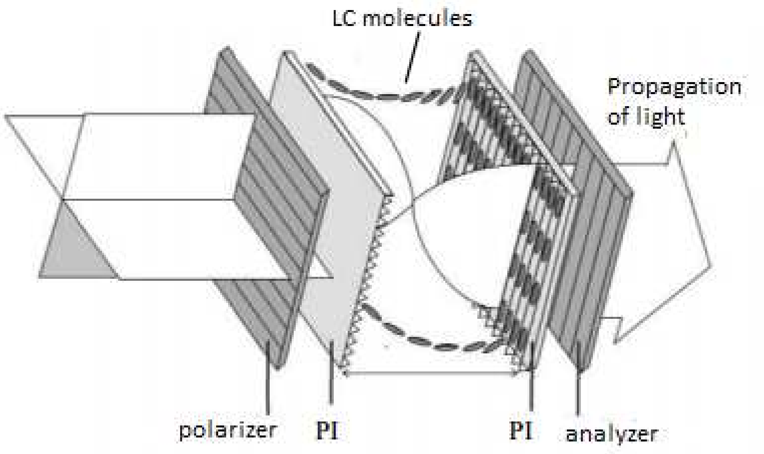
In an LC cell one can observe the so called dichroism phenomena, when the medium has two different, direction dependent refractive index. If the light propagates to the direction defined by the LC molecules, all polarization component propagate with the same $v_o = c/n_o$ speed, where n_o is the ordinary refracrtive index. This direction is called the optical axis of the LC cell. If the light propagates perpendicularly to the direction of the molecules, there are two speed of propagation. The component of light polarized perpendicularly to the optical axis has v_o speed, while the component polarized parallel to the optical axis has $v_e = c/n_e$ speed, where n_e is the extraordinary refractive index. The optical anisotropy is the difference of this to refractive index $\Delta n = n_e - n_o$.

The behavior of the LC cell can be examined by the polarizer filter, one place before the cell (called polarizer) and one placed after (called analizer).

The 90° twisted nematic (TN) LC cell

In the TN LC cell the director of back plate is rotated with 90° with respect to the front plate (Fig.10). Lets assume that the polarizer is parallel to the director of the front plate. The unpolarized incident light becomes linearly polarized after the polarizer.

If a linearly polarized light goes through a 90° TN cell, the polarization of the light follows the twist of direction of the molecules (the polarized light senses only n_e), so the outgoing light is linearly polarized, just its polarization is rotated by 90° (Note: there is rotating mechanism for n_o too). For the normal black (NB) mode of the 90° TN cell the polarization direction of the analizer should be parallel to the polarizators.



10. Fig.

If the voltage connected to the LC cell reaches a critical value U_c, the molecules prefer the be oriented to the direction of the electric field. If the incident beam is polarized with the trenches of the cell, there is no difference, since the light is purely extraordinary.

Although if the incident linearly polarized light is parallel to the cell, but the direction of the polarization enclose $\theta = 45°$ with director of the cell (see Fig.11), than phasedifference (δ) evolves between the two component, since the speed of propagation is different of the ordinary and extraordinary part. In this $\theta = 45°$ setup if the two polarizator are parallel with or perpendicular to each other, the transmission of the system is:

$$T_{\parallel} = 1 - \sin^2 2\theta \sin^2 \frac{\delta}{2} = \cos^2 \frac{\delta}{2},$$

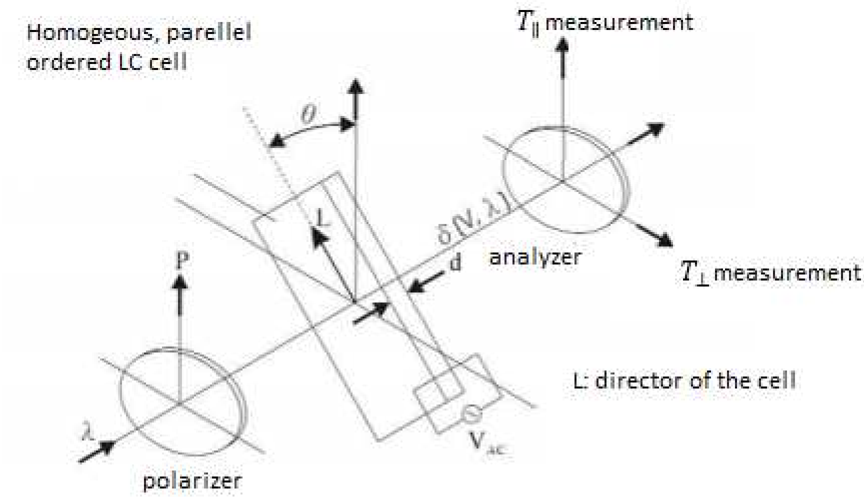
$$T_{\perp} = \sin^2 2\theta \sin^2 \frac{\delta}{2} = \sin^2 \frac{\delta}{2},$$

where $\parallel$ and $\perp$ notes the parallel and perpendicular directon of the polarizator and analizer.

The δ phasedifference can be expressed as:

$$\delta = \frac{2\pi d \Delta n(V, \lambda)}{\lambda}$$

where d is thickness of the LC layer, λ is wavelength of the light, V is the effective value of the AC voltage and Δn (which is a function of λ and V) is the optical anisotropy of the LC cell. It is important to note that V=0, Δn is maximal, and so δ too. It follows that Δn decreases as V increases.



11. Fig.

Other optical devices used during the mearsurement

Laserdiode (LD)

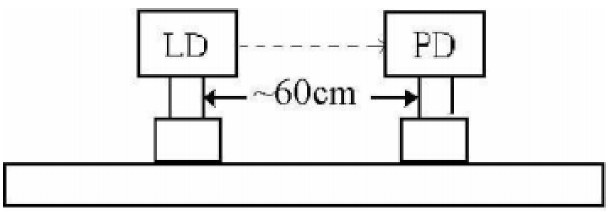
The used light source is a semiconductor laser with 650 nm wavelength. If the current of the laserdiode is higher than a threshold current the diode emits a monochromatic, partially polarized, coherent light. If the current is smaller than the threshold value, the intensity of the emitted light is very small. Above the threshold current the intensity of light is linearly increases with the current up to $I_m$value of the current. If the current is increased further, the emitted intensity decreases (a bit) due to heating of the diode. Optimal working regime is where the current and light-intensity have linear connection. By definition the threshold current I_{th} is the intersection of the current axis and the line fitted to linear regime.

The emitted is partially polarized, the amount of the polarization can be measured by $\beta = i_p/(i_p + i_n)$, where i_p (i_n) are the polarized (unpolarized) intensities respectively.

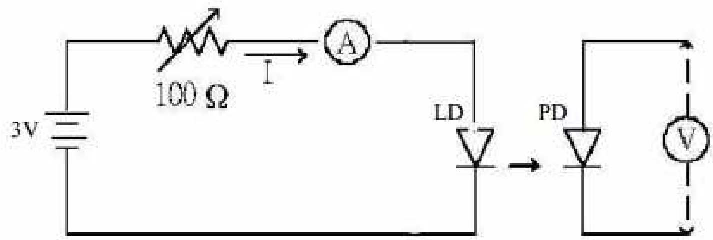
Photodetector (PD)

The photodetector, used during the measurement, consists of a photodiode and a current amplifier. If voltage is connected to the photodiode, than current is generated by incident light. At constant temperature, monochromatic light generates a current propotional to the intensity of the light. The current amplifier transforms this photo-current to a voltage signal. The photodetector has two different amplification mode: high and low. During the measurement only the low mode will be used. Due to the properties of the photodiode, if the intensity of the light is too high, the output voltage saturates at 8V, in this case the photodetector does not work properly. It follow that the optimal working regima of the photodetector is the linear regime. If photodiode reaches the saturation, the photodetector does not indicate the proper light intensity.

The setup and electric circuit diagram of the laserdiode and the photodetector is show non Fig.12-13.



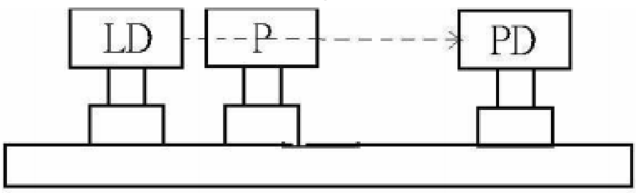
12. Fig.



13. Fig.

Polarizer filter

The polarizer filter, placed in a rotatable holder, linearly polarizes the going-through light. The first filter is usually caller polarizer, the second one is the analyzer, but they have the same structure. The optical setup of the polarizer filters are shown on Fig.14.



14. Fig.

Measurements:

1. *Measuring the focal length with Bessel-method*
   Measure the focal length of the given converging lenses with three different object-image distances, and calculate the average of the measured values.
   Use the halogen lamp as light source, with the blende. Use the blende as the object. Measure the distances with tape.

2. *Measuring the refractive index of glass with total reflection*
   Measure the refractive index of the trapeze-shaped prism.
   Use the halogen lamp as light source, with the blende and the degree-segmented round holder. Right before the round holder, put a slit to the slide-holder. Read the turning angle corresponding to the red and violet outgoing light and use the following formula to calculate the refractive index

$$n = \sqrt{\frac{1 + \cos\varphi \cdot \sin\alpha + (\sin\alpha)^2}{(\sin\varphi)^2}}$$

   $\varphi = 45°$

3. *Examining the polarization of light sources.*
   a) Halogen lamp: measure the intensity of the light of the halogen lamp. Use the blende to narrow the beam and a polarizer filter. With the blende set about 1000 lux intensity of the light. Rotating the polarizer by 10° to 360° measure the intensity. Plot and explain the results.
   b) Measure the light of the laser diode as above, without the blende. Plot and explain the results.

4. *Determining the lattice constant (d) of an optical lattice*
   Put the given optical lattice to the slide-holder and use the laserdiode as light source. Stick a mm scale paper to the screen. Mark the deflection of the light (y) on the mm paper for three different lattice-screen distance (D). Calculate the lattice constant.

$$\frac{n \cdot \lambda}{d} \sim \frac{y}{D}$$

   The wavelength of the light is 650 nm.

5. *Michelson's interferometer and measuring the thermal expansion of ceramics*
   Build the interferometer and set concentrical rings interference pattern, with the help of the supervisor. Start the heating of the ceramic tube (Al_2O) and count the bright-dark transitions in the interference pattern for 30°C of heating. Calculate the thermal expansion coefficient from the measured values. The length of the tube at room temperature can be read from the stand, the wavelength of the light is 650 nm.