Related topics

Polarization of light, birefraction, optical anisotropy, modulation of light, electro-optical modulator, PLZT-element.

Principle and task

Monochromatic, vertically polarized light impinges on a PLZT element (lead-lanthanum-zirconium-titanium compount) which is set in its holder at 45° to the vertical.

An electric field is applied to the PLZT element and causes it to become birefractive. The phase-shift between the normal and the extraordinary light beam behind the PLZT element is recorded as a function of the applied voltage and it is shown that the phase-shift is proportional to the square of the electric field strength respectively of the voltage applied. From the constant of proportionality the Kerr constant is calculated for the PLZT element.

The Kerr effect has usually been demonstrated with nitrobenzene in the past. Since nitrobenzene is very toxic and needs high voltages of some kV the PLZT element which only needs some hundred volts represents an attractive alternative.

Equipment

Kerr cell, PLZT-element	08641.00	1
High voltage supply unit, 0-10 kV	13670.93	1
Laser, He-Ne 1.0 mw, 220 V AC	08181.93	1
Polarising filter, on stem	08610.00	2
Optical profile bench l = 60 cm	08283.00	1
Base f.opt.profile-bench, adjust.	08284.00	2
Slide mount f.opt.pr.-bench, h 30 mm	08286.01	5
Photoelement f. opt. base plt.	08734.00	1
Universal measuring amplifier	13626.93	1
Digital multimeter	07134.00	2
Screened cable, BNC, l 750 mm	07542.11	1
Adapter, BNC-socket/4 mm plug pair	07542.27	1
Connecting cord, 750 mm, red	07362.01	3
Connecting cord, 750 mm, blue	07362.04	2

OPTION for electro-optical modulator

Power frequency generator 1MHz	13650.93	1
Loudspeaker, 8 Ohm/5 kOhm	13765.00	1

Problems

1. The phase-shift between the normal and the extra-ordinary light beam is to be recorded for different voltages applied to the PLZT-element respectively for different electric field strengs.The half-wave voltage $U\left(\frac{\lambda}{2}\right)$ is to be determined.

2. By plotting the square of the applied voltage versus the phase shift between normal and extraordinary beam it is to be shown that the relation between the two quantities is approximately linear. From the slope of the straight line the Kerr constant is to be calculated.

Set-up and procedure

The experiment for the demonstration of the Kerr effect is set up as shown in Fig. 1.

The PLZT element is connected directly to the HV power supply whose voltage can be altered between 0 and 1000 Volt with a sufficiently high precision by using a digital voltmeter branched in parallel to the HV power supply. **Do not exceed 1000 V, this will dammage the PLZT element.** The light source is a He/Ne laser, the power of which is 1 mW.

Important: Before performing any measurement of luminous intensity the He/Ne laser has to be switched on for about one hour to reach its equilibrium in power emission. Moreover, after each appreciable variation of the voltage applied to the

Caution: Never look directly into a non attenuated laser beam

Fig. 1: Experimental set-up for demonstrating the Kerr-effect.
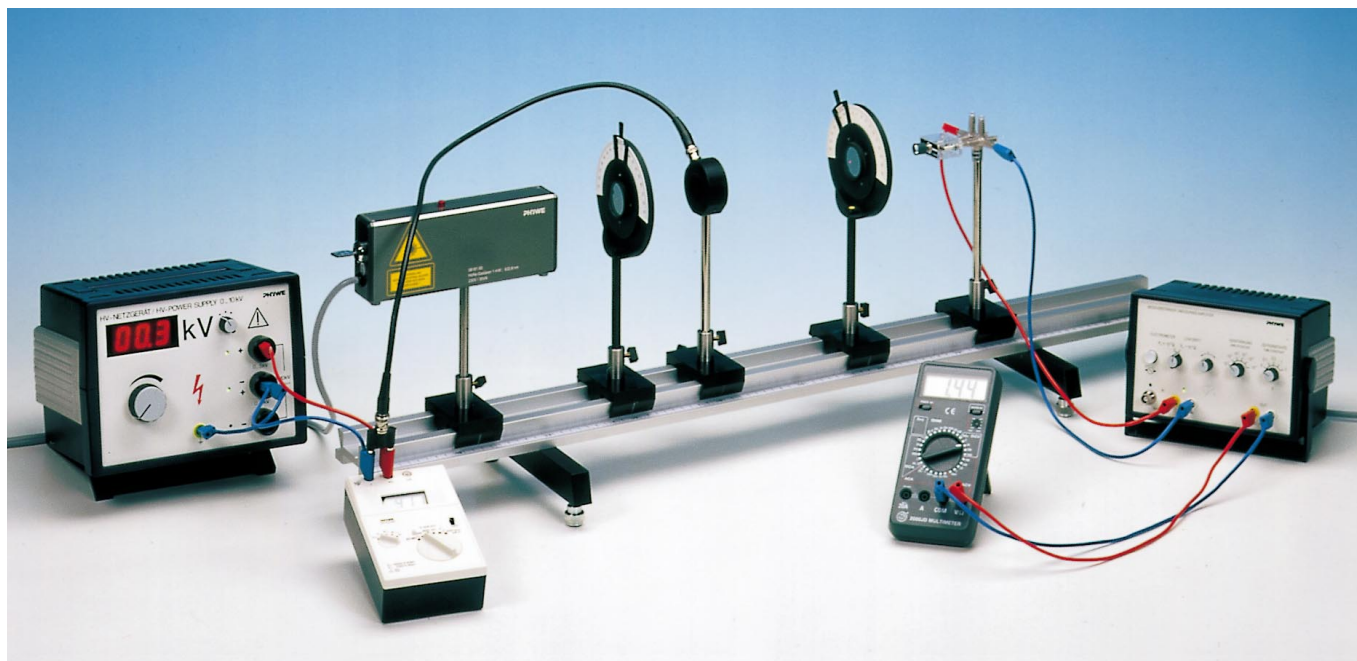
PLZT element about five minutes have to elapse before the crystal structure has readapted and a representative luminous intensity reading can be taken. Needless to say, all measurements have to be performed in a darkened room. The non-polarized portion of the light (background radiation) must also be taken into account. The mesured values depending on the history of the PLZT-element. Also the number of detectable maxima may vary for different elements.

As can be seen from Fig. 1, the light from the He/Ne laser, which is vertically polarized on passing through the polarizer, impinges on the PLZT element which is set in its holder at 45° to the vertical. The incident linearly polarized wave can be regarded as the superimosition of two "in phase" oscillating waves which are polarized, one perpendicularly and the other parallel, to the PLZT element and to the electric field that is applied to the PLZT element.

The two light waves pass through the PLZT element at different speeds. The light wave which oscillates parallel to the electric field of the PLZT element is delayed relative to the light wave which oscillates perpendicularly to the applied electric field of the PLZT element. This produces a phase difference between the two waves and the light which has passed through the Kerr cell (PLZT element) will be elliptically polarized. This results in the analyser, which is located behind the Kerr cell at 90° to the polarizer, no longer being able to extinguish the polarized light.

For a phase difference between the two waves of $\frac{\lambda}{2}$ a linear polarized wave results from the superimposition of the two waves after they have passed through the PLZT element.

This linearly polarized wave is turned by 90° with respect to the direction of incidence, e.g. with respect to the vertical.

The applied voltage is therefore called the "half-wave voltage". In this case the light intensity behind the analyser which is at an angle of 90° to the polarizer will show a maximum.

A silicon photodiode with amplifier is used as the detector for the luminous intensity behind the analyser.

As long ago as 1875 Kerr discovered that a glass plate to which a strong electric field was applied became birefractive. It soon became clear that this effect was not based on deformation caused by the electric field as the same phenomenon was observed in liquids and even in gases.

The PLZT element used in this experiment has the advantage that the birefraction, represented by the Kerr constant, is more than two orders of magnitude larger than for nitrobenzene and voltages of a few hundred volts are sufficient in order to study the electro-optical effects of the ceramic element. This one is transparent for wavelengths from 0.4 to 5.6 μm. Its chemical compositionis here described by the formula Pb 0.9125 La 0.0875 Zr 0.65 Ti 0.3503. With regard to the transmission of light the PLZT element behaves like a transparent polycrystal. For λ = 633 nm its transition ratio is more than 60%. With respect to an applied electric field, it behaves like a ferromagnetic substance which is submitted to a magnetic field.

Within the PLZT element there are already prepolarized domains which grow or which are reorientated by the applied electric field. In this way, the element becomes optically anisotropic respectively birefractive. Regarding the above mentioned electro-optical modulation, it should be pointed out that the element can deal with modulation frequencies of up to 100 kHz.
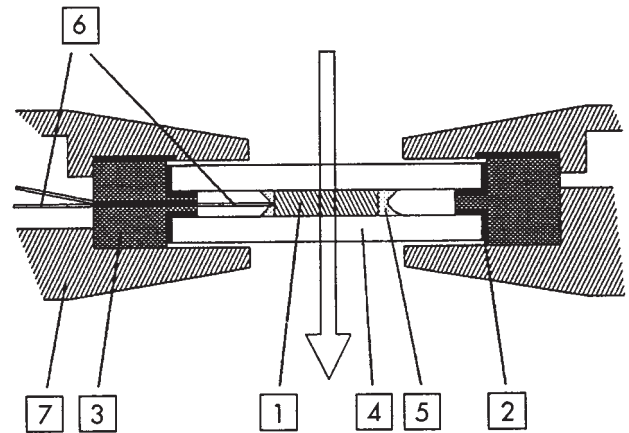
Fig. 2: Cross-section of PLZT element.

Fig. 2 shows a cross-section of the PLZT element. The active element 1 of the modulator is a parallelpiped of height = 8 mm, length = 1.5 mm and width = 1.4 mm.

The width represents the distance between the electrodes. The electric field strength is given by the ratio of voltage applied over the distance between the electrodes. The path of the light beam within the element is equal to the length of the element. Active element (1) is encapsulated using silicon hermetics (2) an isolating ring (3) and glued between two glass plates (4). As optical glue (5) Canadian balsam was used.

Wire (6) are fixed on the electrode faces of the element and connected with BNC socket on frame (7).

Theory and evaluation

The light wave, whose field vector oscillates parallel to the electric field, is called the extraordinary beam whereas the wave oscillating perpendicular to the field is known as the normal beam.

If the corresponding refractive indices are designated by n_{a0} and n_0 and I is the distance in the PLZT element covered by the light, then there is a difference in optical paths for the two waves of

$$I (n_{a0} - n_0)$$

This corresponds to a phase displacement of

$$\Delta = 2\pi \frac{I}{\lambda} (n_{a0} - n_0)$$

where λ is the wavelength of the light in vacuum.
(here: λ = 633 nm)

It can also be shown that the pase displacement is proportional to length I and the square of polarization P. If we anticipate that the polarization is a linear function of the electric field strength E and the proportionality factor is designated by $2\pi K$, then the following relationis obtained:

$$\Delta = 2\pi K I E^2 \tag{2}$$

K is the Kerr constant.

Fig. 3: Relative luminous intensity $\frac{I}{I_0}$ behind the analyser as a function of the voltage U applied to the PLZT element and the phase-shift Δ between normal and extraordinary beam.
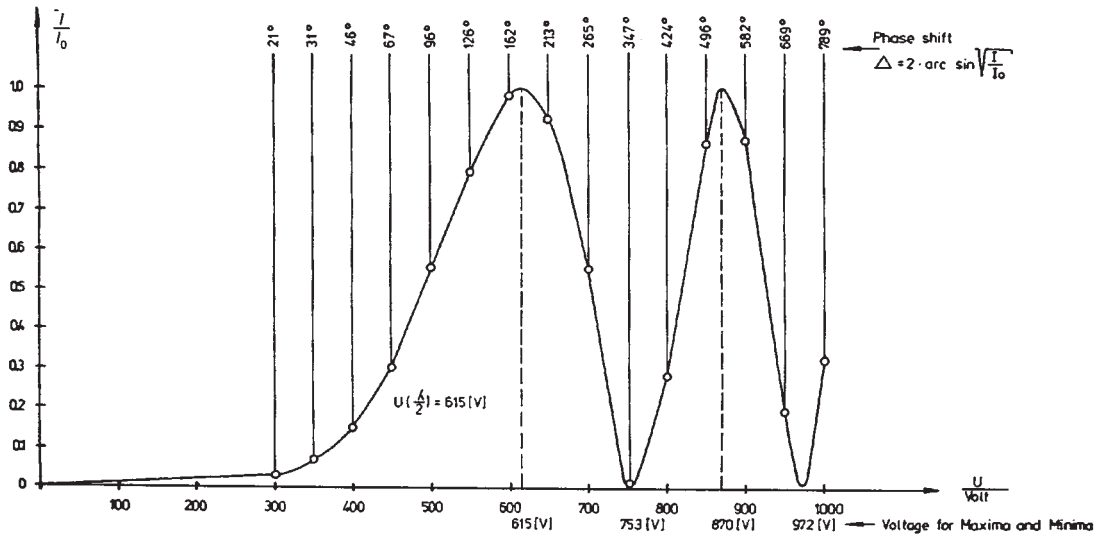
E can be expressed by the applied voltage U and the inter-electrode distance d

$$E = \frac{U}{d} \qquad (3)$$

The luminous intensity I behind the analyser is obtained for the given experimental apparatus (polarizer and analyser crossed and at 45° to the electric field on the PLZT element) from the relationship (1):

$$I = I_0 \sin^2 \frac{\Delta}{2} \qquad (4)$$

I_0 is the luminous behind the analyser when the plarizer and the analyser are aligned in the same direction and the electric field on the PLZT element is zero. After substituting (2) in (4) and using (3), the followings is obtained:

$$I = I_0 \sin^2 \frac{\pi K I U^2}{d^2} \qquad (5)$$

Solving the equation for U^2 gives:

$$U^2 = \frac{d^2}{\pi K I} \cdot \text{arc sin} \sqrt{\frac{I}{I_0}} \qquad (6)$$

By plotting U^2 against $2 \cdot \text{arc sin} \sqrt{\frac{I}{I_0}}$ an approximately straight line is obtained and the Kerr constant can be derived from its slope, because the geometrical dimensions I and d for the Kerr cell (PLZT element) are known.

1. The relative luminous intensity $\frac{I}{I_0}$ behind the analyser is measured as a function of the voltage U applied to the PLZT element.

Tab. 1 shows the measured values. The corresponding graphic is shown in Fig. 3. The phase shift is clearly indicated as well as the voltages for which maxima and minima of luminous intensity are observed. At a voltage of 615 Volt the luminous intensity reaches a maximum for the first time. In this case the

normal and extraordinary beam are phase-shifted by 180°. 615 Volt is therefore the "half-wave voltage". It is a function of the PLZT element compositon and of the temperature.

2. In Fig. 4 the square of the voltage applied to the PLZT element is represented as a function of the phase-shift between normal and extraordinary beam. By linear regression a straight line was found whose slope is $1.36 \cdot 10^3$ (Volt^2/degree).
Using Equ. (6) we find with I = 1.5 mm and d = 1.4 mm a value of

$$K = 2.7 \cdot 10^{-9} \left[\frac{m}{\text{Volt}^2} \right]$$

for the Kerr constant of this element.

U (Volt)	I	$\frac{I}{I_0}$	$\frac{\Delta}{2}$ = arc sin $\sqrt{\frac{I}{I_0}}$
300	0.043	0.034	10.6
350	0.090	0.071	15.5
400	0.190	0.150	22.8
450	0.385	0.304	33.5
500	0.695	0.549	47.8
550	1.005	0.794	63.0
600	1.235	0.976	81.1
650	1.165	0.921	73.7
700	0.685	0.542	47.4
750	0.017	0.013	6.6
800	0.355	0.281	32.0
850	1.085	0.858	67.8
900	1.105	0.874	69.2
950	0.235	0.186	25.5
1000	0.405	0.320	34.3

(I in arbitrary units, I_0 = 1.265)

Tab. 1: Voltage U across the PLZT-element, light intensity I behind the analyser and phase shift $\frac{\Delta}{2}$ between normal and extraodinary beam.

Fig. 4: Square of the voltage applied to the PLZT-element as a function of the phase-shift Δ between normal and extraordinary beam.
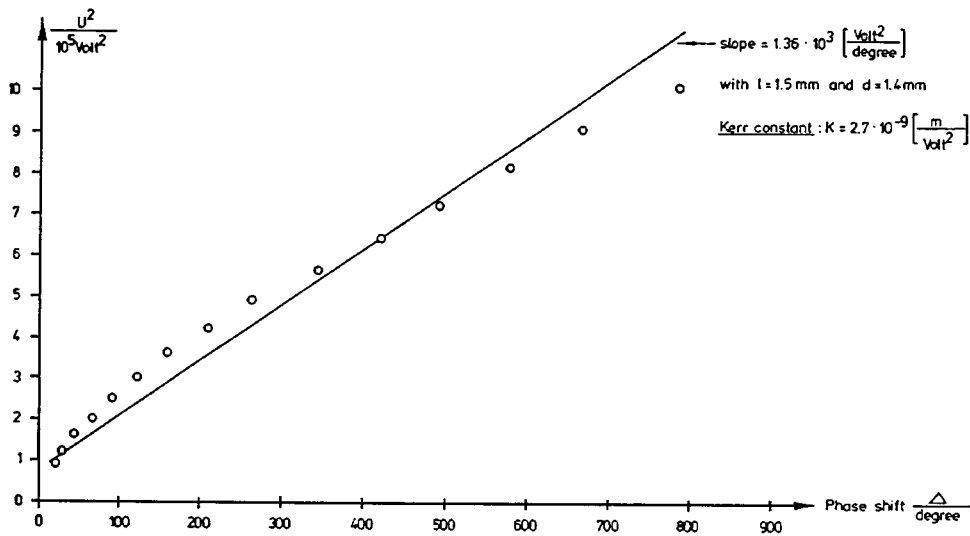
Note

This value may vary for different histories and different elements.

Option

Elekctro-optical modulator

By superposition of an AC-voltage onto the constant electric field the PLZT element is changed into an electro-optical modulator whose functioning is demonstrated acoustically by using an AC-voltage of variable frequency within the audible range.

The output of the power frequency generator is connected in series with a DC voltage of 500 V. The modulated DC voltage is applied to the PLZT element. The voltmeter at the output of the universal amplifier is replaced by a loudspeaker. The output of the universal amplifier (amplification $V = 10^2$) is connected to the 5 Kohn input of the loudspeaker. The amplitude of the frequency generator should be adjusted such that a noise-free sound is heard at the loudspeaker.

By altering the frequency of the generator around 1 kHz, the property of the PLZT element as an electro-optical modulator can be convincingly demonstrated.

Fig. 5: Set up for dectro-optical modulator.