SCIENTIFIC BULLETIN OF THE LODZ UNIVERSITY OF TECHNOLOGY
No. 1224 Physics, Vol. 39 2018

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FREQUENCY DEPENDENCE OF THE KERR CONSTANT IN NYNAS NYTRO 3000 OIL DETERMINED BY THE POLARIMETRIC METHOD

A frequency dependence of the Kerr constant K in transformer oil Nynas Nytro 3000 within a frequency range 117-5017 Hz is determined. An averaged value $(2.30 \pm 0.03)\cdot 10^{-15}$ *m/V*^{2} *for K is obtained. The constant is found to be weakly frequency dependent and approaches its maximum* $2.37\cdot 10^{-15}$ *m/V*^{2} *at about 3000 Hz. The Kerr constant is of comparable value to that observed in other mineral oils employed previously in measurements of the quadratic electro-optic effect and the electrostriction in crystals.*

Keywords: Kerr constant, Nynas Nytro 3000, electric field frequency.

1. INTRODUCTION

A0n electric field applied to isotropic media induces a change in their refractive indices and a rise of birefringence. It is known that isotropic media like liquids are centrosymmetric so all physical phenomena related to odd-order tensors are forbidden by the symmetry. Thus the lowest-order electro-optic effect that may be observed in liquids is the quadratic one. Higher-orders effects are negligibly small and the quadratic is the only one that yields observable changes. In liquids this phenomenon is usually called as Kerr effect. Traditionally, the induced birefringence Δn is described in terms of Kerr constant K as

$$\Delta n = K \lambda E^2, \tag{1}$$

where λ is the light wavelength and E is the electric field strength [1-3]. The Kerr constant is in fact a tensor component thus K depends on directions of applied field and light propagation. The electric field induced changes may be described in a more general way using the following equation

$$B_{ij} = \varepsilon_0 (\varepsilon^{-1})_{ij} = \delta_{ij} n_i + g_{ijkl} E_k E_l \,, \tag{2}$$

where B_{ij} are the components of the impermeability tensor, ε^{-1} is the inverse of dielectric tensor, n_i are the principal refractive indices, g_{ijkl} the components of quadratic electro-optic tensor and E_k, E_l are electric field components. The form of tensor matrix shows that when the field is applied perpendicularly to the direction of light propagating in an isotropic liquid the electric field induced birefringence is [3-5]

$$\Delta n = \tfrac{1}{2} n_o^3 (g_{1111} - g_{1122}) E^2 = K \lambda E^2 \,. \tag{3}$$

Our interest in studies of electro-optic properties of oils is related to the fact that in measurements of quadratic electro-optic coefficients in crystals we usually apply electric fields of strengths up to $1 \cdot 10^6$ V/m. The use of relatively high voltages imposes some precautions against investigated crystals. For example, the samples are often hygroscopic. To protect investigated crystals from moisture and reduce a probability of electric breakdown, the samples are immersed in liquids not solving the crystals. In interferometric experiments the use of a liquid with its refractive index close to the index of crystal suppresses light reflections at the sample faces. An immersing of the sample in the liquid allows also to ignore changes in the optical path resulting from electrostriction [6]. This is particularly important when the electrostriction of the sample is not precisely known. Moreover, an immersion liquid of appropriate viscosity suppresses sample vibrations causing substantial problems in precise interferometric measurements. All these reasons cause that the use of immersion liquids considerably improves the sensitivity of electro-optic measurements in crystals. Immersion liquids introduce an additional contribution to the light beam modulation which originates from a fringing electric field in the sample neighborhood and the Kerr effect of the liquid. Thus the knowledge of electro-optic properties of oils that may be used in investigations of the quadratic electro-optic effect in crystals is important. Mineral transformer oils have all desired properties and this is why we have been researching their properties for a long time (see, e.g. Refs [4, 5]). Moreover, the Kerr effect is interesting from the point of view of the relationship with aging processes of transformer oils [7]. In this work we study the frequency dependence of Kerr effect in a transformer oil Nynas Nytro 3000.

The intensity I of the light passing through a system composed of a Kerr cell and a quarter-wave plate placed between crossed polarizers is given by

$$I = \tfrac{1}{2} I_{\max} (1 - \cos \Gamma) \,, \tag{4}$$

where Γ is the total phase difference introduced by the quarter-wave plate and the liquid in cell. If the oil is subjected to a sinusoidal field $E(t) = E_0 \sin(\Omega t)$, equation (4) takes the form

$$I = \tfrac{1}{2} I_{\max} \left[1 \pm \pi L K E_0^2 (1 - \cos 2\Omega t) \right], \tag{5}$$

where L is the path-length of light in the oil between electrodes and the signs "+" or "–" correspond to perpendicular or parallel azimuths, respectively, of the fast waves in the quarter-wave plate and in the oil. For typical values of the Kerr constant for oils the contribution of the Kerr effect to the DC component I^0 of the intensity I is negligible. Assuming that the voltage U at the output of photodetector is proportional to I, the depth of modulation at the second harmonic of applied field may by written as

$$m = \frac{I^{2\Omega}}{I^0} = \frac{U^{2\Omega}}{U^0} \approx \pi L K E_0^2 \,. \tag{6}$$

In ref. [8] we showed that the sign of Kerr constant may be determined by a special variant of polarimetric technique. In this work only the magnitude of constant K is considered and the symbol K stands for the absolute value of Kerr constant. In Equation (6), $U^{2\Omega}$ is the amplitude of the second harmonic component and U^0 is the constant component in the total output voltage proportional to the emerging light intensity. Hence the Kerr constant is given by

$$K = \frac{m d^2}{\pi L U_{\mathrm{m}}^2} \,, \tag{7}$$

where $U_{\mathrm{m}} = E_0 d$ is the amplitude of the modulating voltage measured between electrodes at distance d.

2. EXPERIMENTAL SETUP

A diagram of the optical and electronic components used in our measurements is shown in Fig. 1. As a source of light a He-Ne laser with wavelength of 632.8 nm was used. A photodiode Thorlabs PDA36A-EC, DC voltmeter Keithley 2000 and a Lock-in voltmeter EG&G 7265DSP were employed to measure components of the emerging light intensity. The electrodes attached to the cell served to apply the electric field perpendicular to the light direction. An internal generator of the Lock-in voltmeter with the amplifier and transformer was employed to provide the high voltage which was recorded by an AC voltmeter Fluke 45 with a probe Tektronix P6015A. The measurements were controlled by a PC computer. The same computer was used for the data acquisition. Parameters of electrodes were as follows: the length $L = (99 \pm 0.05)$ mm and the distance between them $d = (3 \pm 0.05)$ mm.

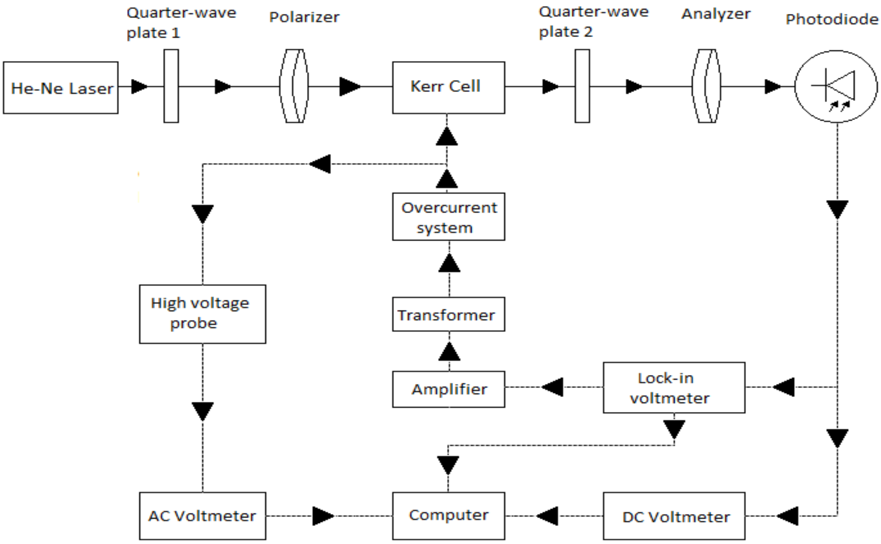


Fig. 1. Diagram of optical and electronic components used in measurements

3. NYNAS NYTRO 3000

The oil Nynas Nytro 3000 is manufactured by a Swedish company Nynas. It is a uninhibited mineral transformer oil without any additives to improve or change its properties. Its properties are typical for mineral transformer oils which makes it useful in the protection of crystal samples against moisture and reduction of the electric breakdown probability. Moreover, the moderate viscosity of the oil makes it useful in interferometric measurements.

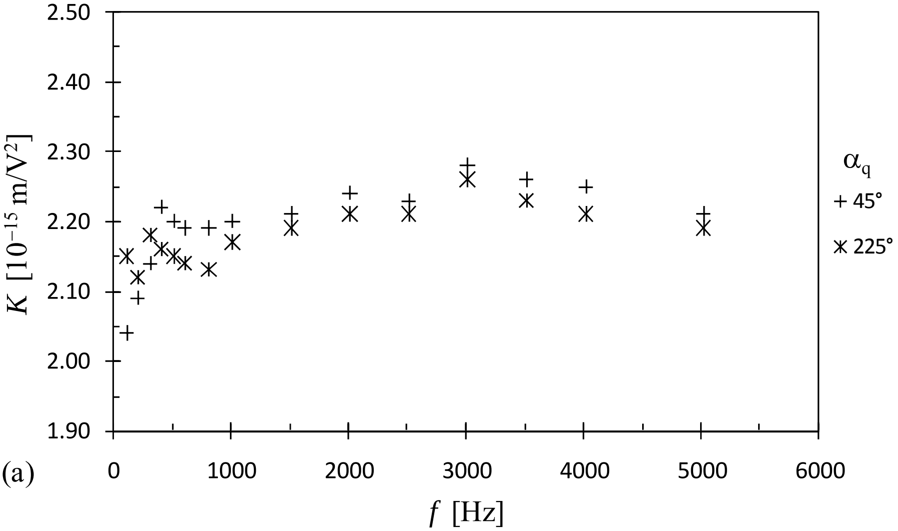
Table 1

Some properties of the Nynas Nytro 3000 [9].

	temperature	average	maximum
density	20 °C	$0.870\ \frac{\text{kg}}{\text{dm}^3}$	$0.895\ \frac{\text{kg}}{\text{dm}^3}$
viscosity	40 °C	$9.5\ \frac{\text{mm}^2}{\text{s}}$	$12.0\ \frac{\text{mm}^2}{\text{s}}$
	–30 °C	$920.0\ \frac{\text{mm}^2}{\text{s}}$	$1800.0\ \frac{\text{mm}^2}{\text{s}}$

4. MEASUREMENTS AND RESULTS

Measurements of the Kerr constant were carried out in the frequency range 117 Hz-5017 Hz. For each frequency, the modulating voltage was changed within the range 500 V-2000 V with a step 100 V. Ten readings were taken for each voltage. In order to protect the results against imperfections of the quarter-wave plate, the readings were repeated for the plate rotated by 90°. The results obtained are illustrated in Fig. 2. It was found that values of the Kerr constant averaged over frequency and two 45° and 225° orientations is 2.188, while for 135° and 315° orientations it is 2.412, which means an offset of 0.224. Our measurements of the used quarter-wave plate along with numerical simulations of the measurement system with an imperfect quarter-wave plate based on the Jones calculus showed that the obtained results can be explained by a deviation of several degrees of the real value of the phase shift introduced by the plate from the ideal value of 90°. On the other hand, imperfections such as dichroism and the optical activity of the quarter-wave plate material have no significant effect. Our numerical simulations also showed that the inaccuracy of the phase difference in the quarter-wave plate leads to a systematic underestimation or overestimation of the K values obtained, depending on the orientation of the faster wave plane. Averaging the results obtained for orientations differing by 90° almost eliminates a systematic error, so there is no need to include it in estimating the uncertainty of the average value. The uncertainty obtained using the K constant values averaged over all orientations α_q for particular frequencies is $0.03\cdot10^{-15}$ m/V^2.



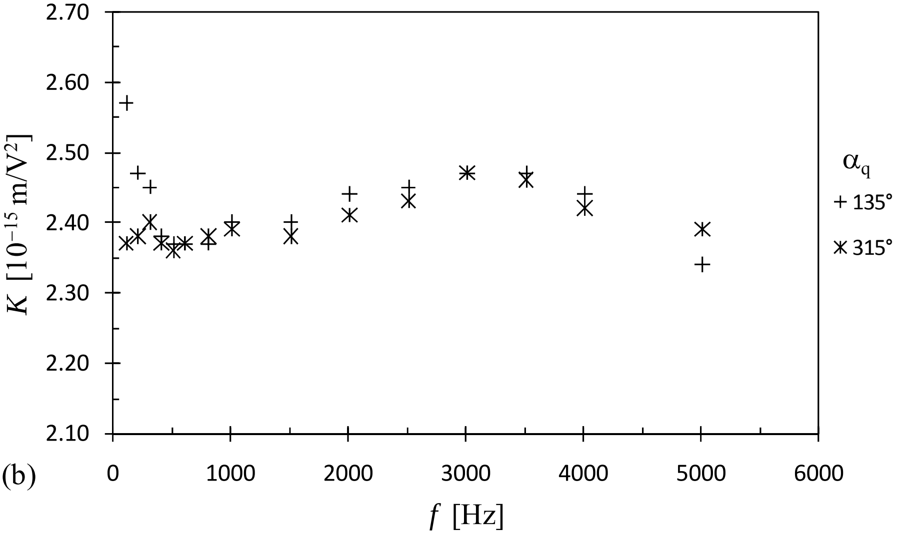


Fig. 2. An example of the dependence of the Kerr constant in Nynas Nytro 3000 oil on the modulating field frequency for different quarter-wave plate orientations α_q: (a) 45° and 225°, (b) 135° and 315°.

The results obtained indicate that the Kerr constant increases slightly up to the frequency of about 3000 Hz and then it starts to decrease. In our opinion, the spread observed for frequencies below 500 Hz may result from effects arising from an orientational ordering of particles in oil [10].

Averaged values of the Kerr constant as related to the modulating field frequency are presented in Fig. 3.

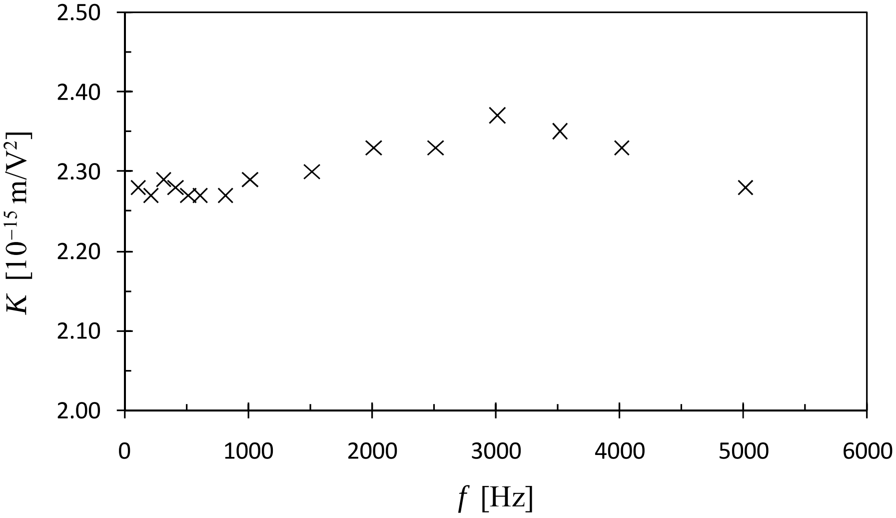


Fig. 3. Averaged values of the Kerr constant in the Nynas Nytro 3000 oil as related to the modulating field frequency.

5. CONCLUSIONS

The results obtained show that in the analyzed frequency range the Kerr constant in the mineral oil Nynas Nytro 3000 is weakly frequency dependent approaching its maximum $2.37 \cdot 10^{-15}$ m/V^2 at about 3000 Hz. Its average value was found to be equal $(2.30 \pm 0.03) \cdot 10^{-15}$ m/V^2. The constant K in the oil is of comparable value to that observed previously in other mineral oils which indicates that the oil may be useful as an immersion liquid in measurements of the quadratic electro-optic effect and electrostriction in crystals.

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CZĘSTOTLIWOŚCIOWA ZALEŻNOŚĆ STAŁEJ KERRA W OLEJU NYNAS NYTRO 3000 OKREŚLONA METODĄ POLARYMETRYCZNĄ

Streszczenie

W zakresie częstotliwości 117 Hz – 5017 Hz przeprowadzono pomiary stałej Kerra *K* oleju transformatorowego Nynas Nytro 3000. Otrzymana średnia wartość stałej wynosi $(2.30 \pm 0.03)\cdot 10^{-15}$ m/V^2 a w okolicach 3000 Hz osiąga ona maksymalną wartość $2.37\cdot 10^{-15}$ m/V^2. Wyniki pokazują, że wielkość stałej Kerra w badanym oleju jest zbliżona do wartości obserwowanych w poprzednio badanych olejach więc może on być wykorzystany jako ciecz immersyjna w pomiarach współczynników kwadratowego efektu elektrooptycznego oraz elektrostrykcji w kryształach.