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APPLICATION OF THE MACH-ZEHNDER INTERFEROMETER TO MEASURE THE QUADRATIC ELECTRO-OPTIC EFFECT IN NONPOLAR LIQUIDS

A modification of Mach-Zehnder interferometer is proposed. It is shown that by introducing an additional time dependent phase shift in one of the interferometer arms, its sensitivity may be significantly increased. The method is applied to measure the quadratic electro-optic effect in transformer oil.

Keywords: Mach-Zehnder interferometer, electro-optic effect in liquids, Kerr constant.

1. INTRODUCTION

Applications of interferometric techniques in measurements of the quadratic electro-optic effect in crystals and liquids are able to provide new valuable data complimentary do results obtained by the polarimetric method. For example, we have previously investigated the contribution of hydrogen bonds to the quadratic electro-optic effect in the paraelectric phase of KDP (KH_2PO_4) type crystals [1]. Usually, nonlinear optical phenomena in the crystals have been described in terms of nonlinear response of PO_4 tetrahedra with neglecting the contribution of hydrogen bonds. In order to check such approach, in reference [1] we have compared temperature dependencies of different components of the quadratic electro-optic tensor. They have been measured employing the polarimetric method. The polarimetric technique is relatively highly sensitive, however, it allows to determine only effective coefficients, i.e. linear combinations of individual coefficients. We have measured two effective coefficients $|n_o^3 g_{1111} - n_e^3 g_{3311}|$ and $n_o^3|g_{3311} - g_{2211}|$, where g_{1111}, g_{2211} and g_{3311} are the individual quadratic electro-optic coefficients and n_o and n_e are the ordinary and extraordinary refractive indices, respectively. One observes that contrary to g_{3311}, where the crystal symmetry allows only for contributions of PO_4 groups, g_{1111} and g_{2211} may result from contribution both of PO_4 groups and hydrogen bonds laying in the *xy* plane. The effective coefficients $|n_o^3 g_{1111} - n_e^3 g_{3311}|$ and $n_o^3 |g_{3311} - g_{2211}|$ have been measured applying the low-frequency electric field along the same direction, i.e. **E** = [*E*,0,0], while the light beam direction was different. The same direction of the electric field has allowed to eliminate a possibility of different changes in the dielectric susceptibility with temperature, and, therefore, different changes in the local field parameter affecting the values of individual coefficients. We have found that the temperature dependencies of the coefficients are different. This result indicates that the contribution of hydrogen bonds cannot be neglected. The results reported in [1] have been obtained for the effective, not individual, quadratic electro-optic coefficients. Therefore, only qualitative conclusions have been drawn. Contrary to traditional polarimetric measurements, interferometric techniques allow for measurements of individual coefficients. Thus, the interferometric methods may be used to obtain quantitative results.

Sensitive interferometric techniques which may be applied in measurements of the quadratic electro-optic effect would be also very useful in investigations of some properties of liquids. Previously, we have investigated the effect of aging of transformer oil on the magnitude and the temperature dependence of its Kerr constant [2]. Recently, we have found that the Kerr constant of food oils also changes with their age. In liquids, the Kerr constant *B* is defined in terms of the birefringence Δn induced in the liquid by the modulating electric field *E*

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

where λ is the light wave length. The birefringence originating from the Kerr effect makes the liquid optically uniaxial with the optic axis parallel to the electric field direction. The form of matrix for the quadratic electro-optic tensor g_{ijkl} in liquids [3] shows that the Kerr constant may be related to two components of g_{ijkl}, namely

$$B = \frac{n_o^3}{2\lambda} \left| g_{1122} - g_{1111} \right| . \tag{2}$$

In our opinion, the knowledge of the magnitude and the temperature dependence of two components g_{2211} and g_{1111} will give an additional information about processes of aging of the oils. One notes that the Kerr constant itself may be measured employing relatively sensitive polarimetric technique, however, the components g_{1111} and g_{1122} may be determined by much less sensitive interferometric methods. Denoting the direction of the modulating electric field as *y*, the changes in the refractive indices of the liquid related to the components of the quadratic electro-optic tensor are given by

$$\Delta n_y = \frac{1}{2} n_o^3 E_y^2 g_{1111} \tag{3}$$

and

$$\Delta n_x = \frac{1}{2} n_o^3 E_y^2 g_{1122} \tag{4}$$

where: n_o is the refractive index in the absence of the electric field and Δn_y and Δn_x are changes in n_o observed for the light beam polarized parallel and perpendicular to the direction of the *y* direction, respectively.

Previously we have used an interferometric method to measure the quadratic electro-optic effect and the electrostriction in crystals. In the measurements an actively stabilized Michelson interferometer has been employed [4, 5]. The construction of stabilized interferometer is complicated. Moreover, in nonpolar liquids the quadratic electro-optic effect is of the order of magnitude 10^{-22} m^2V^{-2}. The low electro-optic response involves the use of relatively long container for the liquid in one of the interferometer arms which makes stabilization more complicated. In this work we propose the use of simple, not stabilized, Mach-Zehnder interferometer. An additional, time dependent phase shift introduced in one of the interferometer arms increases sensitivity of the interferometer allowing for measurements of the quadratic electro-optic tensor in nonpolar liquids.

2. EXPERIMENT

It is known that in the interferometric measurements the sensitivity of the light intensity variations to small changes in optical path length is greatest at a point halfway between the positions of maximum and minimum intensities of the pattern [6]. This point, called often as the middle of interferometer characteristic is denoted in Fig. 1 as P.

In measurements of the quadratic electro-optic effect, the light changes are observed on the second harmonic of the modulating electric field. The measurements should be performed in the vicinity of the point P. In order to avoid the need of stabilization of the interferometer, in the method proposed we introduced an additional time dependent phase difference in one of the interferometer arm. This was obtained by fixing the mirror in one of the interferometer arms on the piezoelectric crystal. The path length in the arm was modulated by applying a sinusoidal electric field to the piezoelectric element. This additional phase difference allowed to sweep the interferometer throughout its transmission characteristic. With the light beam polarized parallel or perpendicular to the direction of the modulating electric field, the readings corresponding to different point of the characteristic, i.e. the light intensity at different points of the inference pattern were recorded. We recorded the intensity

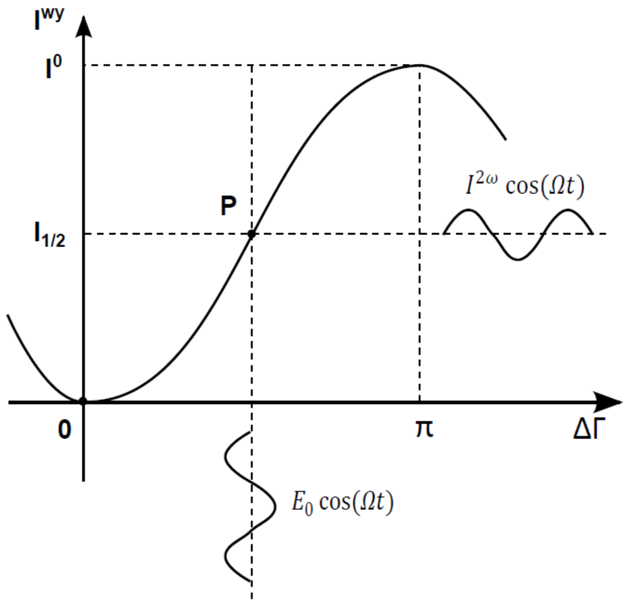

Fig. 1. Interferometer characteristic i.e. the dependence of the output light intensity I^{wy} on the phase shift $\Delta\Gamma$. The point P denotes the phase shift, providing the maximum of sensitivity independent of electro-optically induced phase changes

$I^{2\Omega}$ observed on the second harmonic of the modulating electric field and the constant component of the light beam intensity I^0. The measurements were performed for the transformer oil Orlen TRAFO EN. The results obtained for different orientation of polarizers are presented in Figs. 2 and 3.

The coefficients g_{1111} and g_{2211} were obtained by processing the readings and taking into account the data obtained in the vicinity of the point P, i.e. when $I^{2\Omega}$ and I^0 reached the maximum and minimum, respectively. Components of the quadratic electro-optic effect are related to the experimental data as [4, 7]

$$g_{1111} = \frac{2m_y^{2\Omega}\lambda d^2}{\pi l n_o^3 U_0^2}, \tag{5}$$

and

$$g_{1122} = \frac{2m_x^{2\Omega}\lambda d^2}{\pi l n_o^3 U_0^2}, \tag{6}$$

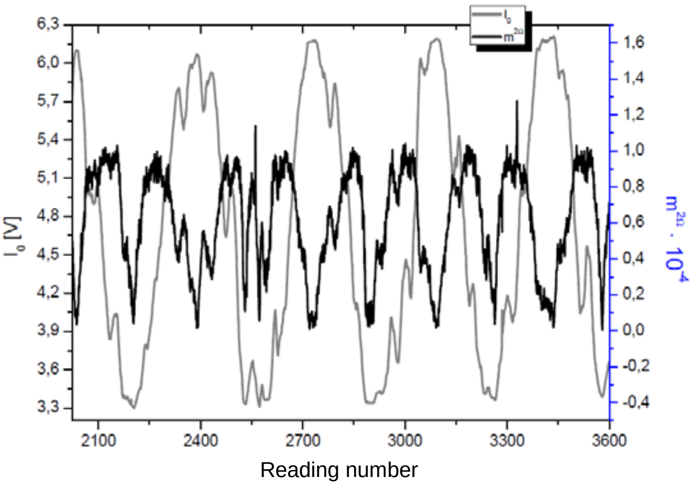

Fig. 2. The dependence of the the constant component of the light beam intensity I^0 and of the modulation index $m_{y,x}^{2\Omega}$ (see Eq. (7) below) on the reading number. Polarization of the light beam is parallel to the direction of the modulating electric field

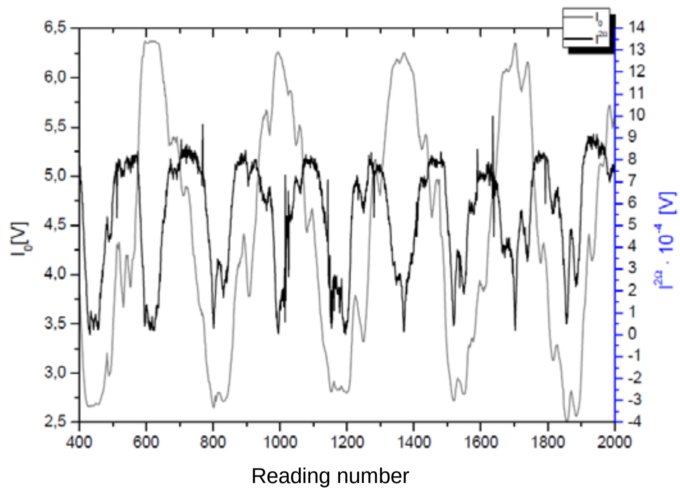

Fig. 3. The dependence of the the constant component of the light beam intensity I^0 and of the modulation index $m_{y,x}^{2\Omega}$ (see Eq. (7) below) on the reading number. Polarization of the light beam is perpendicular to the direction of the modulating electric field

In Eqs. (5) and (6), $m_{y,x}^{2\Omega}$ is the modulation index

$$m_{y,x}^{2\Omega} = \frac{I_{y,x}^{2\Omega}}{I_{y,x}^{0}}, \tag{7}$$

λ is the light wave length, d is the distance between electrodes, l is the path length of the light in the oil and U_0 is the amplitude of the modulating voltage.

In the measurements, the He-Ne laser was used (λ = 0.63 μm), l = 98.2 mm, d = 5.26 mm, n_o = 1.484 and the amplitude of the modulating voltage of the frequency 430Hz was up to U_0 = 2500 kV. The results obtained for the oil Orlen TRAFO EN are: $g_{1111} = 6.8 \cdot 10^{-22}$ m^2V^{-2} and $g_{1122} = 11.2 \cdot 10^{-22}$ m^2V^{-2}. Expecting that the signs of g_{1111} and g_{1122} are different, one obtains the effective coefficient $g_{eff} = |g_{1111} - g_{1122}|$ to be $18 \cdot 10^{-22}$ m^2V^{-2}. This value may be compared to $g_{eff} = 45 \cdot 10^{-22}$ m^2V^{-2} obtained in this work by polarimetric technique. The difference suggests the necessity of additional calibration. This may be performed by providing modulation of the path length in of one of interferometer arms using piezoelectric crystals with known piezoelectric constants.

3. CONCLUSIONS

The quadratic electro-optic coefficients in the transformer oil are one order of magnitude lower than these observed in crystals (KDP, ADP). Nevertheless, the results indicate that the application of the method allows for measurement of the quadratic electro-optic effect in nonpolar liquids, despite the lack of active stabilization of the interferometer.

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ZASTOSOWANIE INTERFEROMETRU MACHA-ZEHNDERA DO POMIARÓW KWADRATOWEGO EFEKTU ELEKTROOPTYCZNEGO W CIECZACH NIEPOLARNYCH

Streszczenie

Zaproponowano metodę pomiaru kwadratowego efektu elektrooptycznego w cieczach przy wykorzystaniu interferometru Macha-Zehndera. Pokazano, że dodatkowa modulacja fazy w jednym z ramion interferometru znacząco zwiększa czułość pomiaru. Metodę zastosowano do pomiaru składowych tensora kwadratowego efektu elektrooptycznego w oleju transformatorowym.