Optica Applicata, Vol. XIV, No. 4, 1984

Pencil object beam light heterodyne interferometer

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A model of the heterodyne interferometer for testing of transparent objects, capable to provide diagrams of distribution of the optical path difference with the sensitivity equal to $\lambda/100$, is shown in the elaboration. Influence of various factors on the measurement accuracy is presented. The results of the experiments involved prove that the instrument may be used in the following cases: analyses of optical specimens, measurements of thickness of film layers and analyses of alternations of factor of refractive index of liquids. The significant advantages are as follows: high sensitivity, high resistance against external factors and extremely high simplicity of the mechanico-optical system.

1. Introduction

The measurements by interference may be used to determine the values of the phase shift of the light wave introduced by the object examined and on this basis to obtain the information about the object itself. In the classical interferometers used to test the materials the information about the changes in optical path in the objects under test is presented in the form of interference fringes. In many cases the interferogram does not represent the occurring phase perturbation uniquely and exactly enough. Some methods and devices have been then elaborated which allow us to reconstruct truly the phase distributions and to represent them in the form of graphs or pseudo-three-dimensional maps. One of these methods is the computer analysis of the interference pattern [1, 2]. Such a process requires an application of special programming and mathematical processing of a large number of data, which elongates the measurement duration. Another solution which assures obtaining very exact (of order of $\lambda/100$) and unique results in the form of maps or graphs is a heterodyne interferometer. In this article a heterodyne interferometer for transport examination has been described. In spite of the typical solutions [3, 4] in this system an unexpanded He-Ne laser beam has been used. The laboratory setup presented allowed us to perform the graphs of optical path changes (both in time and space) with the sensitivity of $\lambda/100$ ($\lambda = 0.6328$ μm).

2. Heterodyne interferometry

Optical heterodyning is understood as an intensity modulation of the light beam appearing due to interference superposition of two coherent waves of different frequencies:

$$A_1 = A_{01}\exp i[\omega t - \varphi_0], \tag{1}$$

$$A_2 = A_{02}\exp i[(\omega+\Omega)t - \varphi_1] \tag{2}$$

where: A_{01}, A_{02} – amplitudes of the coherent component wave,
$\omega = 2\pi f$, f – frequency of the light wave,
$\Omega = 2\pi\Delta f$, Δ – frequency difference of the interfering waves,
φ_0, φ_1 – phases of the component light waves:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos[\Omega t - (\varphi_1 - \varphi_0)] \tag{3}$$

(where: I – intensity of the beam under test, I_1, I_2 – intensities of the component waves). A photodetector fast enough and irradiated by such a beam gives an electric signal of differential frequency Δf and phase Φ uniquely connected with the phase difference of the interfering waves

$$a = a_0\cos(\Omega t - \Phi) \tag{4}$$

(a_0 – amplitude of the electric signal). Assuming the phase of one of the components (reference wave) for a reference value to be $\varphi_0 = 0$, the phase of the other component of the light wave (object wave) may be measured by determining the phase of the electric signal.

The heterodyne method of the phase detection, as compared to the classical methods offers the following fundamental advantages:

– high sensitivity of optical path difference measurement,

– linear relation between the phase of the light wave and the measured phase of the electric signal,

– unique distinction of the phase change sign (differentiation of *the hill* from *the valley*).

– small sensitivity to changes of light source intensity.

So far optical heterodyning has been applied to measure the phase of acoustic waves [5], in microinterferometer [6] an in broad-beam interferometers for optical element testing [3, 4]. The broad-beam heterodyne interferometer should be composed of large optical elements performed exactly and, additionally, an electronic compensation of errors introduced by the system [3] is required. The application of the unexpanded laser-beam allowed a very simple and stable mechanic-optic design of the interferometer which offers high accuracy of measurement.

3. Pencil object beam light heterodyne interferometer

Below, the principle of an interferometer operation is presented basing on the scheme in Fig. 1. Pencil He-Ne laser is introduced to an acousto-optic modulator AM controlled by a sinusoidal signal from the high-frequency generator.

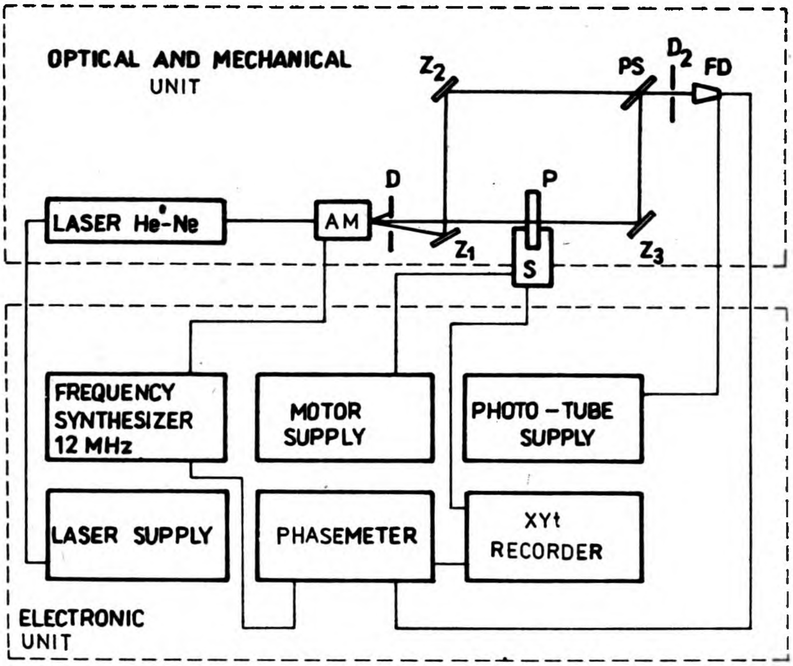

Fig. 1. Scheme of the pencil object beam light heterodyne interferometer

Due to light interaction with the acoustic wave and the spatial filtration with the diaphragm D_1 two beams emerge from the modulator: one of zero diffraction order and the other of first diffraction order. The values of the frequency shift of the first diffraction order are equal to the frequency of the signal feeding the modulator [7]. Both the beams – the object beam passing through the examined object P and the reference beam – are directed by the mirrors Z_1, Z_2, Z_3 and after an interference superposition on the light dividing plate PS they irradiate the photodetector PD. The diaphragm D_2 restricts the diameter of the region, from which the information is acquired, which results in an increased spatial resolution. The phase of the object beam, carrying the information about the optical path in the examined object P, determines uniquely the phase of the signal received from the photodetector. The measurement is performed with a phasemeter as a result of comparison of the signal from the photodetector with a master signal from the generator feeding the modulator AM. The value of the phase in the form of an analog signal controls the displacement Y of the plotter. The X displacement is coupled to transversal (with respect to the axis of the analysing beam) movement of the stage S, to which the examined object is fastened. The system presented allows us to perform either the graphs of the phase deformation at selected sections of the analysed transparent objects or when making use of the t movement of the plotter to analyse changes in the time.

Basing on the given optical scheme a laboratory model has been produced which is shown in the photograph (Fig. 2). In this setup LG–200 He-Ne laser

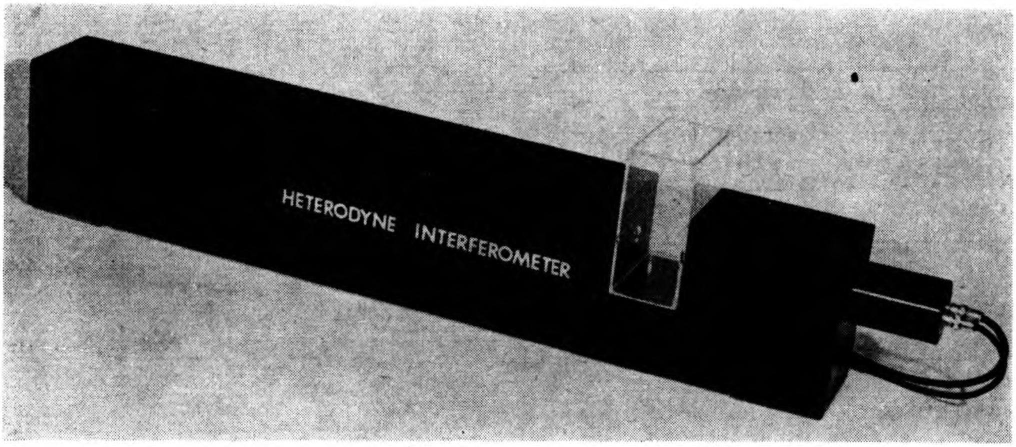

Fig. 2. Model of a heterodyne interferometer for transparent object testing

of 1.5 mW output of COBRABiD make was applied. The acousto-optic modulator, produced in Institute of Design of Precise and Optical Instruments, Warsaw Technical University, gave the frequency shift $\Delta f = 12$ MHz. The mirrors and the light-dividing plate were positioned in a modified configuration of Mach-Zehnder interferometer. The supporting structure of the interferometer [8] and the holders of the optical elements [9] assure very stable behaviours of the fixed positions. For the detection of the optical signal BPYP–51 avalanche photodiode was used. The object was fixed in a holder allowing the precise choice of the examined section. The scanning along the horizontal axis was realized by using a moving stage controlled electronically. Clearence between the analysing beam and the base of the measuring chamber amounted to 35 mm, while the length of that chamber was 65 mm. The laser, the modulator, the optical system and the photodetector were imbedded in one housing thus creating a device of dimensions $108 \times 160 \times 875$ mm. The phase was measured with the help of a Hewlett-Packard phasemeter. The phase deformations were presented with a Riken Denshi plotter.

4. Restrictions in a measurement accuracy of a heterodyne interferometer. Influence of the external factors

The measurement possibilities of the heterodyne interferometer may be considered by estimating both the accuracy of the optical path difference measurement and the spatial and time resolution of the device. The spatial resolution is limited by diffraction effects and the useful diameter of the measuring beam (in the model presented $D_2 = 0.4$ mm). The time resolution is restricted by the measurement time of the phasemeter (in the system $tp_{max} = 30$ ms). In the case of typical optical elements of small (below the wavelength of the effective light) but extended deformations as well as for slow (in comparison with the measurement time) changes in optical path the accuracy of the phase difference measurement becomes a dominating parameter. The latter depends mainly on the accuracy of the applied way of phase difference measurement of two electric signals as well as on the random values (influence of the external factors) of the interfering phases of light beams

4.1. Restrictions in the electronic phase measurement accuracy

The heterodyne method of detection consists in the measurement of relative phase difference of two electric signals – the difference at the origin of the measurement is assumed to be a reference value. The accuracy of such a measurement is close to the resolution of the phasemeter and exceeds many times the measurement accuracy of the absolute phase difference of two signals feeding the device input. The applied phasemeter allowed us to differentiate the phase shift $\sim 0.5°$, which corresponds to the optical path difference $\lambda/720$. The determination of the time difference of transition through the zero of both the measurement and reference signals is the basis of the measurement with the phasemeter. The spread of the measurement signal evoked by the noise (the noise of the master signal being negligible) introduces the error in the determination of the transition time through the zero and this causes the error of phase measurement to appear. The determination of the signal-to-noise power ratio SNR allows us to evaluate the error caused by the noise [3]

$$\Delta\varphi = \frac{360}{2\pi\sqrt{2\mathrm{SNR}}} \tag{5}$$

where $\Delta\varphi$ – phase error in the arc measure

$$\mathrm{SNR} = V_0^2/2\bar{v}^2,$$

V_0 – signal amplitude from photodetector, $\bar{v}$ – value of the r.m.s. noise. In the setup presented the received value of SNR was $\geqslant 27$ dB which gives a maximal error of phase difference measurement $\Delta\varphi \cong 1.8$, corresponding to the error of optical path difference $\Delta l = \lambda/200$.

The analysis presented shows that the accuracy of the applied method of the phase difference measurement of two electric signals is restricted, in the first order, by the quality of the measurement. The noise is introduced mainly by the photodetector and the amplifier. This causes also some pulsing of the laser beam intensity. When a laser of a large number of longitudinal modes of frequencies less than the upper cut-off of the electronic detector and measurement is applied, the intensity modulation evoked by heterodyning between the longitudinal laser modes must be encountered.

4.2. Restrictions of the phase measurement accuracy evoked by the external factors

The practical accuracy of the measurement with the interferometer is limited by the random phase shift of the interfering beams. These shifts are evoked mainly by the temperature changes, air rotation and mechanical vibrations. The respective constructions of the supporting plate, optical element holders and interferometer adjustment on the damping bench plate diminished the sensitivity of the system to mechanical vibration. The influence of the external disturbances on the measurement accuracy for the produced interferometer

Fig. 3. Influence of the external perturbations on the random phase shifts of the interfering light beams. Assuring special stabilization conditions of the external parameters (a), typical perturbations under normal measurement conditions: effect of systematic phase change – *the swimming zero* (b), directing of a low flux of heated air on the measurement chamber housing (c), striking the bench plate (d), approaching the hand to the object beam (e), air rotation around the open measuring chamber (f)

model is illustrated in the successive graphs (Figs. 3a–f). They show the (time) changes in the phases of the interfering beams for an empty measuring chamber. The Fig. 3a was produced during 5 min. time while special stability conditions for external parameters were assured:

— the system was stabilized for about 1 hour,

— during the measurement all movements in the lab were stopped,

— the measurement was performed in the period of considerable diminishing of all kinds of traffic in the whole building of which the lab is only a part.

The wavy character of the drawn line corresponding to the changes of the optical path difference $\Delta l \geqslant \lambda/200$ may be attributed to both the errors of the electronic measurement of the phase as well as to the influence of the external factors. This restricts the minimal value of the deformation ΔL which may be reconstructed by the system. When assuming $L = 2\Delta l$ it may be expected that, when assuring the special measurement conditions to be fulfilled, the optical path difference $\Delta L = \lambda/100$ may be imaged uniquely. The line presented in the Fig. 3b illustrates the perturbation which occured for the normal typical conditions of measurement, i.e.:

— stabilization time of the system 0.5 h,

— during the measurement all the unnecessary movements were stopped in the vicinity of the measuring chamber.

Under such conditions some random perturbations reached the extreme values of $\sim \lambda/50$. Besides, a systematic change of the optical path is visibly evoked, most probably, by the thermal changes in dimensions of the interferometer elements. On the basis of the graph the error is determined which should be encountered when performing a single measurement $\Delta l_1 = \lambda/50$. An increase of the measurement number, for instance, by making several graphs of identical cross-sections of the same element allows us to distinguish the examined deformations of values close to $\lambda/100$ from the random perturbations.

The next graphs (Figs. 3c–f) show the reaction of the system to a characteristic external perturbations like:

— a weak flux of the air heated (up to 36°C) directed toward the measurement chamber housing (Fig. 3c),

— striking the bench plate (Fig. 3d),

— approach of the hand to the measuring beam repeated twice (Fig. 3e),

— causing an air rotation around the opened measuring chamber (Fig. 3f).

5. Application examples of the heterodyne interferometer with a pencil object beam

5.1. Testing the deformation of optical elements

In Figures 4–6 the graphs of deformations at selected cross-sections of the plane-parallel plates performed with a broad-beam interferometer have been

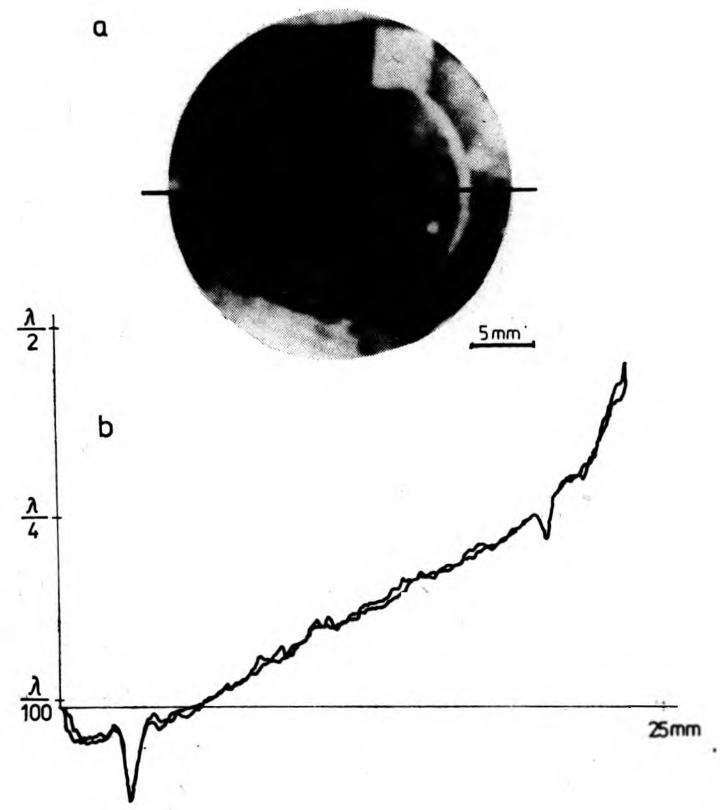

Fig. 4. Deformation of the cuvette walls. Interferogram produced with a classical interferometer (a), graph of the deformation in the given cross-section obtained in the heterodyne interferometer (b)

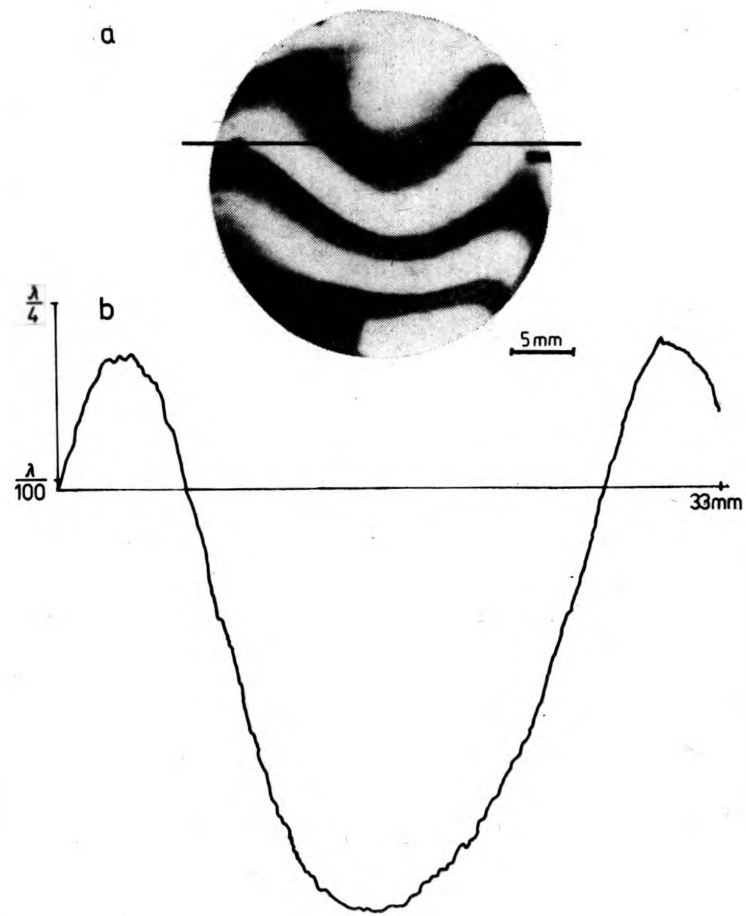

Fig. 5. Distinction of deformation of *hill-* from *valley*-type. Interferogram (a), graph from heterodyne interferometer (b)

illustrated. The cross-sections analysed are marked by black line in the interferogram. Figure 4 illustrates the deformations of the walls of the cuvette used in the interference measurements. In order to average the results and to differentiate the random perturbations from the existing deformations the graph (Fig. 4b) has been made twice. The interferogram in Fig. 5a does not ifnorm uniquely about the deformation imaged. Figure 5b allows us to diferfentiate in an evident way *the hill* from *the valley.* In Fig. 6b the changes

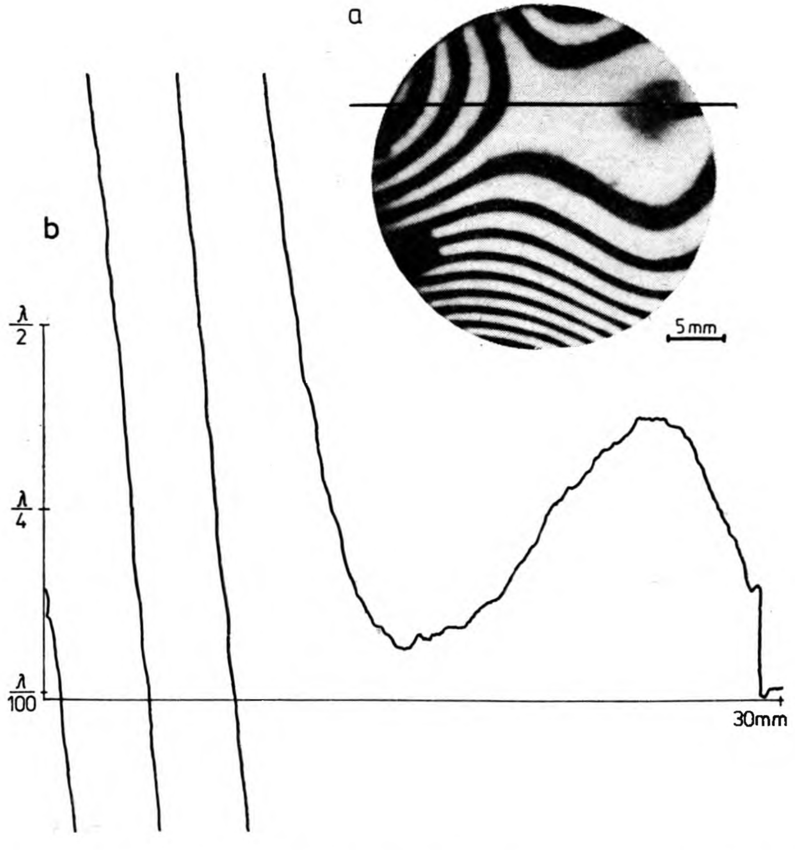

Fig. 6. Presentation of deformation exceeding the value of λ in the marked cross-section Interferogram (a), graph of the heterodyne interferometer (b)

of the optical path are shown which shift the phase of the light by a value of $\Delta\Phi > 360°$. In this case the measuring range of the phasemeter was exceeded which resulted in a shifting of the plotter pen in an opposite extreme position.

5.2. Deformation of the optical element due to its fastening

The plane parallel plate of 50 mm diameter and of 11 mm thickness has been fastened in the way shown schematically in Fig. 7a. The graphs in Figs. 7b and 7c are performed along the denoted cross-section at minimal (Fig. 7b) and slightly increased (Fig. 7c – continuous line) pressure of the fastening screws.

The deformations in the section evoked by the screw pressure are shown as a difference between the continuous and broken lines in Fig. 7c.

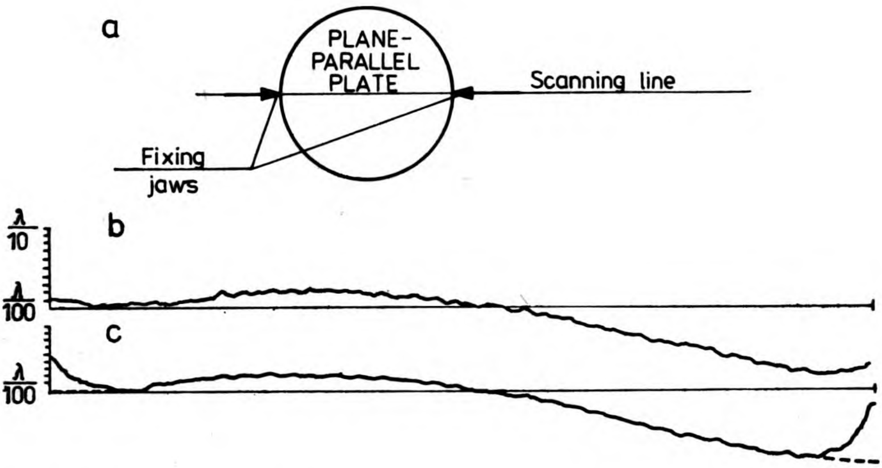

Fig. 7. Influence of the fastening method on the optical element deformation. Scheme of fastening (a), graph performed for low pressure of the screws (b), graph performed for increased pressure of the screws (c). The deformations are shown as the differences between the continuous and broken lines

5.3. Measurement of the thin-layer thickness

The photograph shown in Figure 8a presents an interferogram of the plane-parallel plate with a deposited SiO_2 strip. By using the heterodyne interferometer the graphs in Figs. 8b and 8c were made which illustrate the thickness and the thickness changes of the deposited layer as well as the substrate deformation. By many-fold repeating the graph (section A–A) the maximal light difference of the reconstructed shape never exceeded $\lambda/90$. When taking account of the refractive index of SiO_2, $n = 1.46$, the thickness of the deposited layer in the A–A cross-section amounted to $d = 0.246 \pm 0.008$ µm.

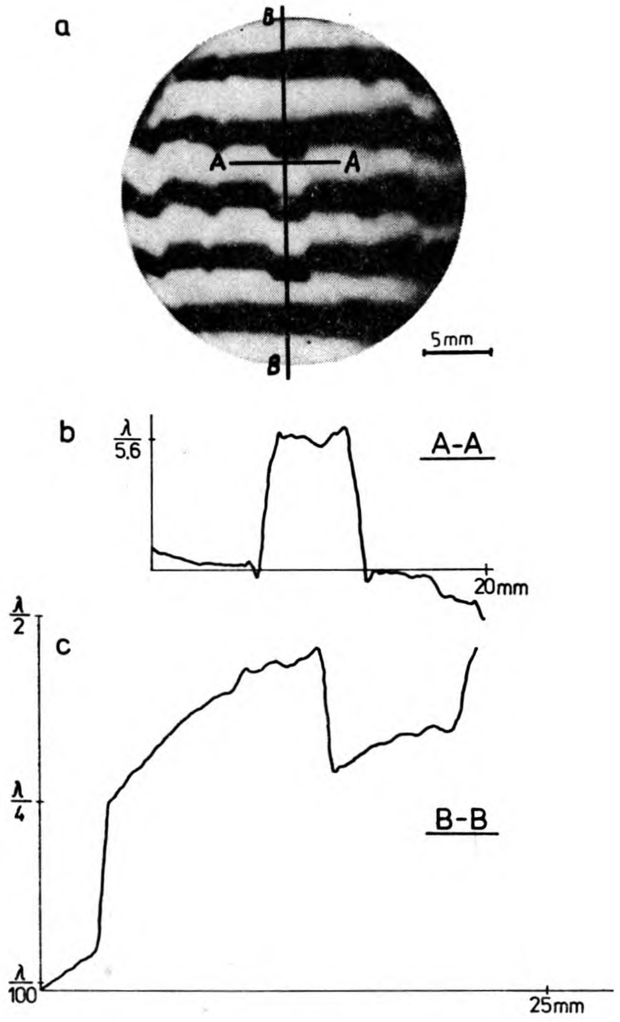

Fig. 8. The measurement of the thin-film thickness. Interferogram of the plate with deposited SiO_2 strip (a), graphs produced in a heterodyne interferometer (b, c)

5.4. Registration of the changes in the refractive index of the fluid

A small crystal of NaCl was put into a measuring cuvette with water (Fig. 9). The graph 9a shows the changes in refractive index which occurred during the first three minutes in the region of the analysing laser beam.

6. Concluding remarks

The purpose of this work was to elaborate an interferometer system for the material examination of high measurement accuracy and uniqueness.

As a result the described heterodyne interferometer for testing transparent objects was designed which assures the measurement of the optical path dif-

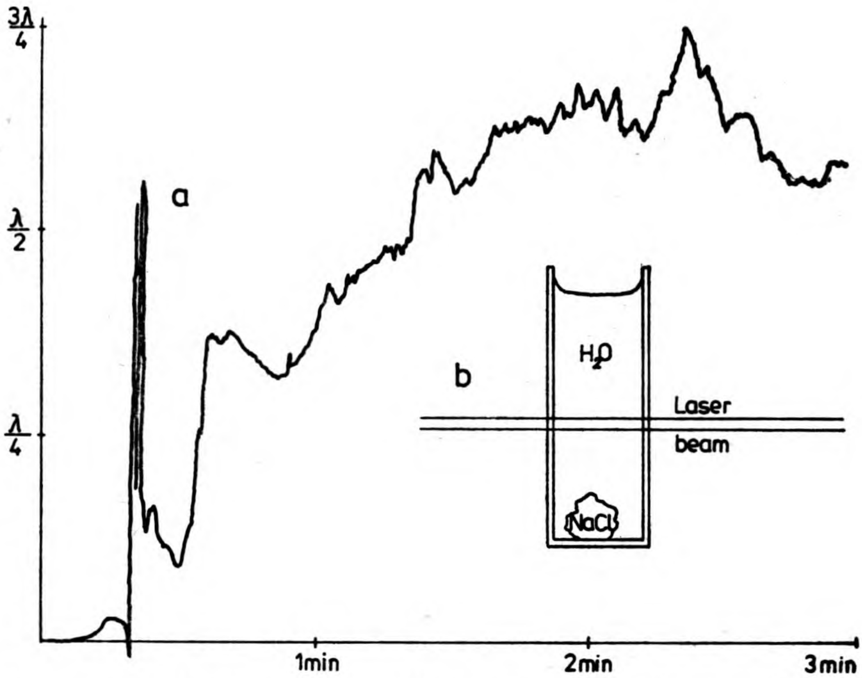

Fig. 9. Changes in refractive index of the solution evoked by the salt dissolution. Graph produced with the heterodyne interferometer (a), scheme of the cuvette with the tested solution (b)

ference with the accuracy of $\lambda/100$. The measurement results are presented in the form of unique, readable graphs of the phase deformations in the selected cross-sections of the sample or in the form of the graphs of time changes of the optical path. The interferometer consists of an electronic unit a mechanic-optic unit with the detection system and a movable stage provided with a sample holder. Unlike in the typical solutions an unexpanded laser beam was used in the system. This has allowed us to avoid many problems which occur during the performance and exploitation of the expanded-beam interferometers. The suitable construction enabled to produce the mechanic-optic unit in the form of a small and compact device. The following readily available elements constitute the device:

– low-power He-Ne laser of small dimensions requiring no adjustment,
– simple acousto-optic modulator,
– small, low-quality optical elements,
– simple system of optical signal detection.

This device is light, portable and adjustable by a single person. It is characterized by low sensitivity to disadjustment during the time or due to transportation. The dimensions of the measurement chamber of the interferometer allow an examination of the whole region of the sample of maximal diameter $D = 70$ mm. A production of the setup to examine greater samples does not constitute any essential problem. When comparing with the up-to-now used constructions the following basic shortcomings of the interferometer should be named: impossibility of quick visualization of the whole region of deformation and the necessity of scanning with the element under test. Another inconvenience is also due to the complexity of the electronic system making the cost of the whole instrument higher.

Taking account of all the features of the presented heterodyne interferometer it may be believed that it will be used, in addition to the classical expanded-beam interferometer, both in research laboratories and in optical industry producing particularly exact optical elements. Another advantage seems to follow from the coupling of the device with the microprocessor. This will allow us to replace the graphs by pseudo-three-dimensional maps of the analysed deformations. The possibility of the real-time supplying of the results in the form of electric signal and the respective features of the mechanic-optic constructions suggest also a possible exploitation of the setup in an automated system of measurement and control.

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Received April 20, 1984

Гетеродинный интерферометр с узким предметным пучком

Представлена модель гетеродинного интерферометра для испытания прозрачных объектов, при помощи которого возможно изготовить диаграмму распределения разности оптических путей с чувствительностью $\lambda/100$. Оценено влияние разнородных факторов на точность измерения. Представленные результаты экспериментов подсказывают следующие возможности применения этого устройства: испытание оптических элементов, измерение толщины тонких слоев, анализ изменения коэффициента преломления жидкости. Основными достоинствами интерферометра являются: большая чувствительность, небольшая восприимчивость к внешним факторам и исключительно простая механически-оптическая система.