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An application of the methods of coherent optics to investigations of acoustical fields

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Optical reflection methods used in measurements of parameters and visualization of acoustic surface waves (ASW) are presented. The efficiency of the methods is illustrated by the results of ASW parameter measurements in a lithium iodate single crystal of cut z, propagation along the x-axis, phase velocity $v = 2220 \pm 11$ m/s and ASW amplitude $\delta = 2.60 \pm 0.01$ nm. The travelling acoustic wave has been visualized in two ways: by spatial filtering and by using the method of acoustical stroboscopy giving a stationary image of the wavefronts.

Introduction

One of the newer tendencies in applications of the coherent light diffraction on the acoustic waves is the diagnostics of the microwave acoustics elements.

There in most case are the delay lines, filters, resonators employing the acoustic surface waves (ASW) of Rayleigh type. This kind of waves propagating in the surface layer evoke the periodical variations of the refractive index and the rippling of the surface. Both of these effects cause the diffraction of light.

From the analysis of the intensity direction and frequency of the spatially diffracted light beam we may conclude about the value of the examined acoustical field parameters.

The subjects of the measurement and investigations are: the velocity and the length of the acoustic wave, amplitude of the rippled surface direction of propagation and power distribution in the cross-section. The acoustic wavelength is of order of some to several micrometers and its measurement is not difficult.

However, the amplitude (δ_1) of the surface rippling is proportional to the power of the acoustical field and is as low as several nanometers and the measurement accuracy is usually a measure of the efficiency of the method applied. In our case the method employed rendered a possibility of measuring the values of deflexion amplitude in the surface with the accuracy below 0.1 nm.

In this paper the way of measuring the parameters and visualization of the acoustic surface wave field in lithium iodate single crystals is shown. The visualization of the wavefronts on the examined crystal surface has been achieved. The method presented may be used to examination of the solid state surfaces independently of their transparency.

The measurement of ASW parameters by the optical reflection method

The light beam 2D diameter falling at the angle θ_i onto the wave surface is subject to both refraction and difraction (fig. 1). The diffraction distribution of the electric field of the beam reflected from the rippled surface is described by the following

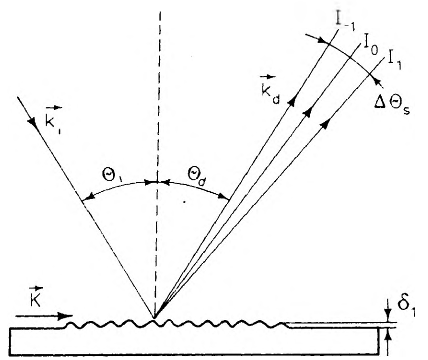

Fig. 1. Light diffraction on the acoustic surface wave

relation [1]:

$$E_2(p) = \sum_{m=-\infty}^{+\infty} A_m \exp j[(\omega+m\Omega)t-k_d R_0], \tag{1}$$

where:

$$A_m = j^{(m+1)} A(E_0 R) F J_m(\alpha_1),$$

$A(E_0, R)$ — constant depending upon the incident electric field amplitude and the reflection coefficient,

$$F = \frac{\sin[(\gamma - mK)] \dfrac{D}{\cos\theta_i}}{\left[(\gamma - mK)\dfrac{D}{\cos\theta_i}\right]}$$ — function determining the angular distribution of the light intensity maximum,

$J_m(\alpha_1)$ — Bessel function determining the light intensity distribution in the diffraction fringes depending upon the ASW amplitude,

$\gamma = k_d \sin\theta_d - k_i \sin\theta_i$,

$\alpha_1 = (k_d \cos\theta_d + k_i \cos\theta_i)\delta_1$,

δ_1 — amplitude ASW,

$\omega + m\Omega$ — frequency of the diffracted light wave shifted by the frequency of the acoustical wave Ω,

m — diffraction order.

The maximum of the electric field distribution is achieved when $F = 1$. Hence, after rearranging the expression for the angle of diffraction of m-th order, it takes the form

$$\Delta\theta_m = \frac{mK}{k_i \cos\theta_i}. \tag{2}$$

From the formula (2) after substituting $m = \pm 1$ and taking into account of $K = 2\pi\nu/V$ we obtain the formula for the phase velocity of ASW

$$V = \frac{2\lambda\nu}{\Delta\theta_s \cos\theta_i} \quad [\mathrm{m/s}], \tag{3}$$

and the acoustical wavelength

$$\Lambda = \frac{V}{\nu} = \frac{2\lambda}{\Delta\theta_s \cos\theta_i} \quad [\mu\mathrm{m}], \tag{4}$$

where:

$\Delta\theta_s = 2\Delta\theta$ (fig. 1) — separation angle (in radians) between the $+1$ and -1 diffraction orders,

ν — ASW frequency (in megahertz),

λ — light wavelength.

The light intensity in ± 1 diffraction orders amount to

$$I_{d\pm 1} = E_2 E_2^* = I_0 R^2 J_1^2 (2k_i \delta_1 \cos\theta_i). \tag{5}$$

By restricting our attention to the first term in the development of the $J_1(\alpha_1)$ Bessel function into series we may write (5) in the form

$$I_{d\pm 1} = I_0 R^2 k_i^2 \cos^2\theta_i \delta_1^2, \tag{6}$$

hence the ASW amplitude is

$$\delta_1 = \frac{\lambda}{2\pi\cos\theta_i} \sqrt{\frac{I_{d\pm 1}}{I_i}}, \tag{7}$$

where:

δ_1 — ASW amplitude (deflexion along the z-axis),

$I_{d\pm 1}$ — light intensity in $+1$ and -1 diffraction orders,

$I_i = I_0 R^2$ — light intensity after reflection from the sample surface without ASW.

As it follows from the formulae (3), (4), (7) the measuring system should be adjusted to the measurement of the separation angle $\Delta\theta_s$, the angle incidence θ_i and the diffraction efficiency $\eta = I_{d\pm 1}/I_i$.

To facilitate the electronic processing of the measured magnitudes the signal affecting the surface has been modulated by the rectangular wave of 10 kHz frequency. The scheme of the measuring system is shown in fig. 2.

The light beam from the laser focused by the optical system passes through the acoustooptical modulator, where it is subjected to diffraction and deviation. A rotator polaryzer enables a rotation of the polarization vector with respect to the sample surface. The light is subject to diffraction on this sample surface accros which the ASW propagates. This results in a spatial separation of the subsequent diffraction orders, whereafter $+1$ and -1 orders are detected with a photomultiplier. The signal from the photomultiplier is applied to the homodyne nanovoltometer to which a reference signal is also provided by a rectangular wave generators.

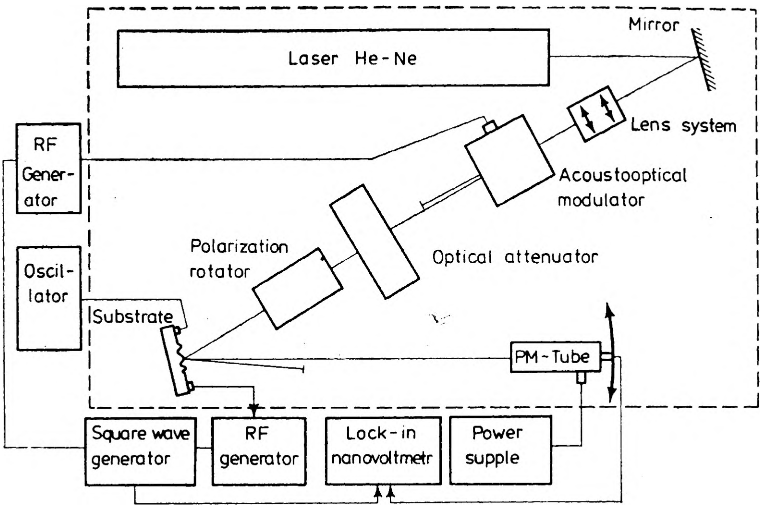

Fig. 2. The scheme of the measuring system for the ASW parameters

When applying such a system the signals from the photomultiplier may be detected below the noise level.

The light incidence angle θ_i is measured on a goniometer with the accuracy of 1′. The angle of separation $\Delta\theta_s$ which decides about the accuracy of the calculation value of the phase velocity of ASW is measured as the angle of photomultipliers rotation (coupled with a goniometer) between two maximal indications of nanometer corresponding to $+1$ and -1 diffraction orders (fig. 1).

In order to increase the measurement accuracy the photomultiplier rotation is coupled with a helipot which is joined, in turn, with XY recorder. The signal from the helipot is applied to the X-input of the recorder, while the signal from the photomultiplier is applied to the Y-input. The determination of the separation angle from the graph increases the measurement accuracy up to 0.3′, which for the measured values of first order gives the accuracy of 0.5%.

The measurement of diffraction efficiency is carried out by the comparsion in two stages:

1° The acoustooptical modulator is fed by a continuous high-frequency signal while the sample is fed by a high-frequency signal modulated by a rectangular wave of 10 kHz of frequency. The diffracted wave from the modulator falling on a sample with ASW is subject to diffraction. By detecting $+1$ and -1 orders of diffraction we obtain the voltage $U_{\pm 1}$ on the photomultiplier measured in the homodyne nanovoltometers system; this voltage is proportional to the intensity of given diffraction order.

2° The acoustooptical modulator is fed by the high-frequency signal of amplitude as mentioned in 1° and modulated by the rectangular wave of 10 kHz frequency. The feeding of the sample is switched out. The modulated beam is reflected only from the motionless surface of the sample and is directed onto the photomultiplier. The variable optical attenuator is used to reduce the radiation intensity to the voltage level $U_{\pm 1}$. The read-out of the attenuation value corresponds to the diffraction efficiency value with the accuracy of 1%.

The particular feature distinguishing the described system among the systems known from the literature [2-5] is the application of an acoustooptical modulator in place a mechanical chopper, which improves the measurement accuracy and eliminates the problems of stabilizing and synchronizing the chopper. The identical light beam modulation obtained for both the case of ASW modulation in the 1° stage and the case of the acousto-optical modulator at the 2° stage enables to use the homodyne detection.

Examplified results of the measurements carried out for ASW with $\nu = 30$ MHz and propagating within the single crystal of lithium niobate with the *zx*-cut, and covered with a 0.4 μm layers of gold or aluminium are given below:

The measured quantities:

— light beam incidence angle on the sample $\theta_i = 8°15'(\pm 1)$,

— separation angle $\Delta\theta_s = 1$ $(\pm 0.3')$,

— diffraction efficiency $\eta = 6.78 \cdot 10^{-4}$ (1% error).

ASW parameters

— phase velocity $v = 2220 \pm 11$ m/s,

— a coustic wavelength $\Lambda = 73.8 \pm 0.4$ μm,

— ASW amplitude $\delta = 2.60 \pm 0.01$ nm.

The optical method of acoustic wave velocity measurement allows to achieve in a simple way high accuracy of order of 0.5% m To achieve such measurement accuracy by the other methods a complex apparature should be employed.

The measurement accuracy of absolute values for ASW amplitude achievable with this method depends exclusively on the accuracy of measurement of light beam attenuation.

In the system an optical attenuator, composed of two elements: a steady one of 10^{-4} attenuation and a variable one of polarizer-analyser type has been applied, which gave the measurement accuracy as high as 0.01 nm.

Visualization of travelling acoustic surface wave by the method of spatial filtration

This method allows to obtain an image of the crystal surface with a propagating acoustic wave on the TV monitor has the form of bright striae. It consists in applying spatial filtering of the diffraction orders of the beam reflected from the wave surface [6, 7]. The scheme of the visualizing system is shown in fig. 3.

The parallel light beam from the He-Ne laser of 8 mW power expanded by the optical system falls onto the sample surface illuminating the region of ASW propagation jointly with the transducers.

The sample surface deformed under the influence of ASW affects the light in the way similar to the movable diffraction grating, thus in the image focus plane of the lens L_3 we get the diffraction pattern, i.e. there appear the diffraction orders

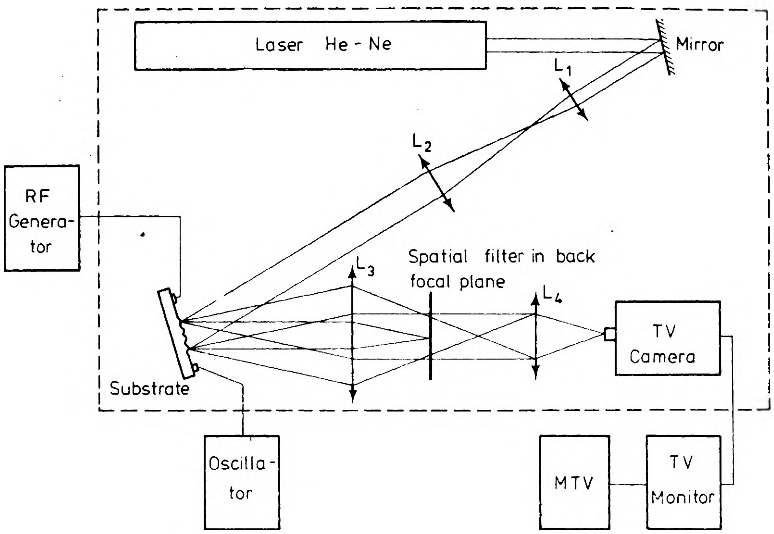

Fig. 3. Scheme of the system for the surface wave visualization by the method of spatial filtering

$m = 0, \pm 1$. Simultaneously, the light suffers from diffraction at the stationarity structure of transducers interdigital generating also the diffraction orders $m = 0, \pm 1', \pm 2' \ldots$

The frequency of the diffraction grating produced by the transducer structure is twice as high as that the acoustic wave, which gives the spatial separation of the fringes ± 1 and $\pm 1'$. Depending on the need we may filter the fringes containing information about the surface (± 1) or about the transducer structure ($\pm 1'$) or both jointly.

The image created by the optical system L_4 of the surface is observed on the TV monitor and recorded on a video-tape-recorder. The television receiver system

Fig. 4. The sample of $LiJO_3$ crystal covered with a reflecting Al layer without the acoustic wave. On the right and left hand sides of the photograph a contours of the interdigital transducers is visible. The bright spots represents the point defects on the surface layer.

of the image enables the observation of dynamic phenomena in the real time. The figs. 4 and 5 present the visualized acoustic wave travelling accross the $LiJO_3$ crystal surface.

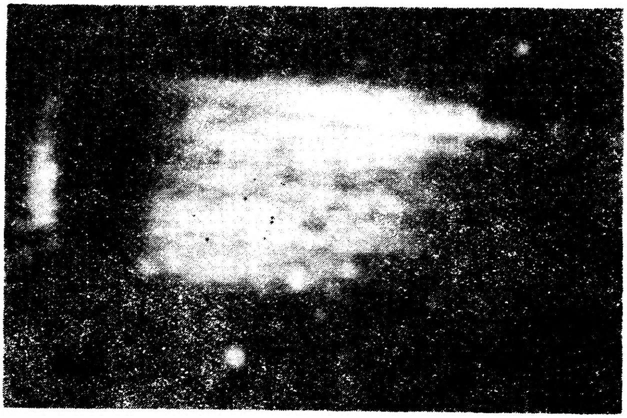

Fig. 5. The sample of $LiJO_3$ with ASW. The travelling surface wave is visualized in the form of bright striae. On the left hand side a transducer. The resonance frequency of the transducer is $\nu = 34.2$MHz

A photometric analysis of the ASW images obtained with this visualizing technique allows to measure the distribution of the relative amplitude of the surface wave and to determine the direction of the energy flux propagation of ASW.

The least observable amplitude depends on the noise level, the spatial filter characteristics and the crystal quality. The image of ASW may be obtained both for the surface covered with a reflecting layer and the transparent surfaces. An application of this method to the visualization of samples of higher acoustic frequency does not render any difficulties.

Visualization of ASW with the method of acoustic stroboscopy

By using this method we may observe a motionless phase image of the travelling acoustic wave. The image brightness is proportional to the acoustic field strength on the surface examined [8, 9].

The stationary image of the wave-front is obtained by illuminating the crystal surface with ASW with a light beam previously modulated. This modulation of the incident beam must be strictly synchronized with the wave perturbing the examined surface.

The scheme of the stroboscopic visualization system is presented in fig. 6. The light from the He—Ne laser is directed to a bulk acoustooptic modulator, while the $\pm$first orders of diffraction are focused by the L_2, L_3 objective on the crystal surface with ASW, on which a new diffraction occurs.

The objective L_4 and the filter separate spatially and filter the respective diffraction orders. The objectives L_5 transfer the appearing image of the acoustic wave on the TV camera. The image is displayed on a TV monitor.

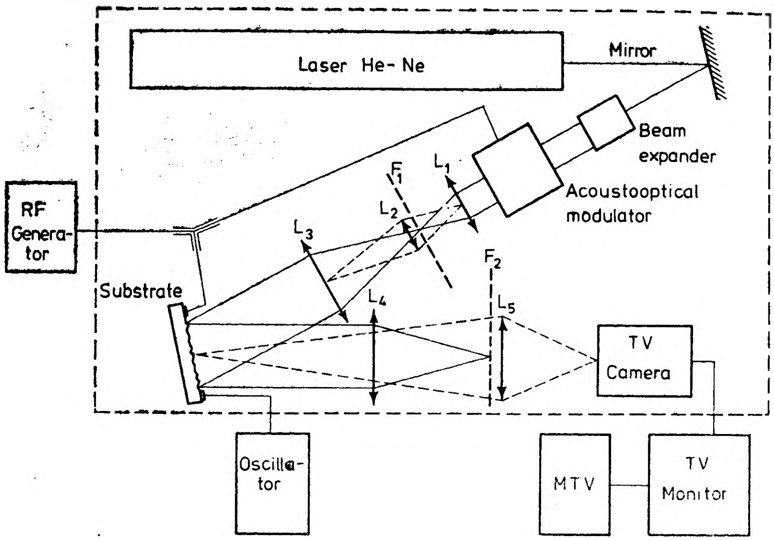

Fig. 6. The scheme of the ASW visualizing system by the stroboscopic method

The synchronous feeding of the bulk acoustooptic modulator and the sample with ASW is a condition of obtaining a stationary image of the wave-fronts (the principle of acoustic stroboscopy).

The analytic descriptions of the image formation is the following:

The refractive index of the medium perturbed with the acoustic wave has the form

$$n(x, t) = n_0 = \Delta n \cos(\Omega t - Kx), \tag{8}$$

where:

n_0 — equivalent refractive index,

Ω — frequency of the acoustic wave,

$K = 2\pi/\Lambda$ — acoustic wave number.

The light wave $E = E_0 e^{-j\omega t}$ falling on the acoustooptic modulator is subject to diffraction and a optical separation of the modes. By restricting our attention to the diffraction orders $m = 0, \pm 1$, we may describe the electric field behind the acoustooptic modulator by the formula

$$E = e^{-j\omega t}[1 + ja_1 \cos(\Omega t - Kx)]. \tag{9}$$

The expression in the brackets is the transmittance T_1 of the medium with travelling acoustic wave, a_1 being the amplitude of the acoustic bulk wave.

By filtering diffraction orders $m = \pm 1$ the expression (9) takes the form

$$E = ja_1 \cos(\Omega t - Kx)^{-j\omega t}. \tag{10}$$

Such a signal falls upon the surface perturbed with the surface wave of the frequency signal equal to Ω. The modulation of the light reflected from the surface with ASW may be defined by the transmittance T_2

$$T_2 = 1 + j\delta_1 \cos(\Omega t - Kx), \tag{11}$$

where δ_1 is the amplitude of the surface wave. By taking account of the optical system magnification g we obtain behind the modulator

$$E = \left[ja_1 \cos\left(\Omega t - \frac{Kx}{g}\right) - \frac{1}{2} a_1 \delta_1 \cos\left(2\Omega t - Kx\left(1 + \frac{1}{2}\right)\right) - \frac{1}{2} a_1 \delta_1 \cos Kx\left(1 - \frac{1}{g}\right)\right] e^{-j\omega t}. \tag{12}$$

The last component in the expression (12) corresponds to two overlapping orders containing no acoustic frequencies. After stopping the other orders we obtain

$$E = \frac{1}{2} a_1 \delta_1 \cos\left[Kx\left(1 - \frac{1}{g}\right)\right] e^{-j\omega t}. \tag{13}$$

As the light intensity $I \sim |E|^2 = E \cdot E^*$ we obtain the formula for the screen illumination

$$I \sim \frac{1}{4} a_1^2 \delta_1^2 \cos^2\left[Kx\left(1 - \frac{1}{g}\right)\right]. \tag{14}$$

The intensity distribution does not depend upon the time t, and the factor $\cos^2 Kx$ corresponds to the phase distribution of the travelling acoustic surface wave.

If the amplitude a_1 is constant the image intensity is proportional to the surface perturbance δ_1^2. In figs. 7-10 some examples of the visualization of the acoustic surface wave travelling in the lithium iodate crystal covered with a Al layer are given. The working frequency of the system amounted to $\nu = 34.75$ MHz.

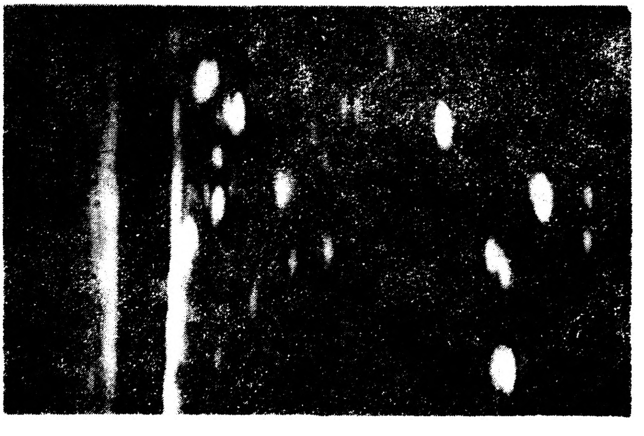

Fig. 7. The $LiJO_3$ sample without the surface wave. On the left hand side a contour of the transducer as well as the edge of the reflecting surface are visible. The arrows denote the light scattered on the reflecting surface defects

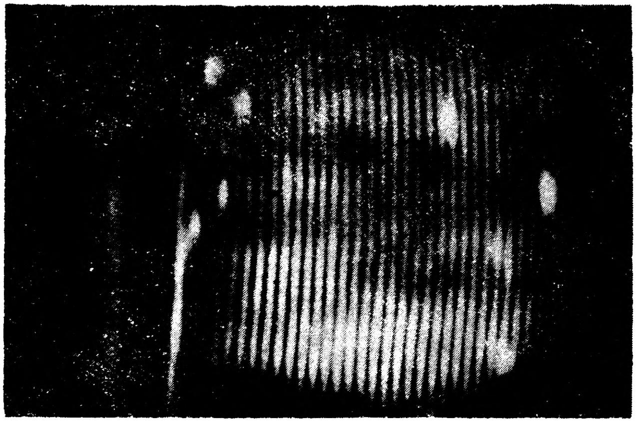

Fig. 8. The $LiJO_3$ sample without ASW. The image of forming wave-front is visible. The distances between the successive intensity maxima correspond to $1/2\Lambda$

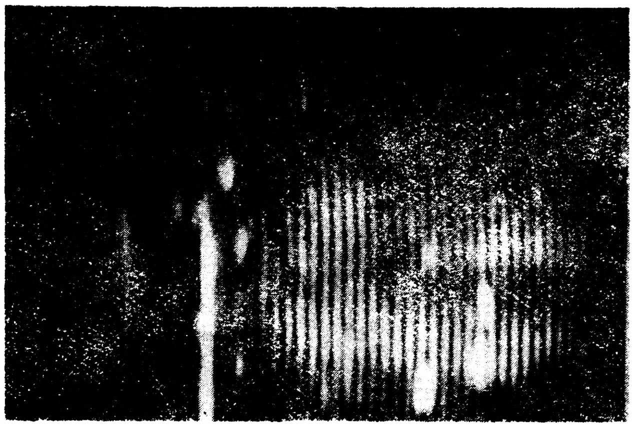

Fig. 9. Upper edge of the acoustic flux corresponding to the surface wave

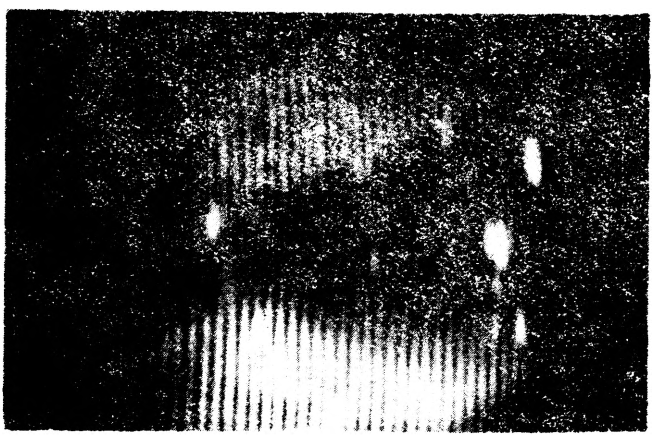

Fig. 10. A partial damage of the transducer – dark spot indicates the decay of the wave generation

As it follows from the photographs presented the stroboscopic method gives the possibility of a direct observation of the phase variation image as the wave travels. This refers in particular to the observations of the effect wave-front formation in the field near to the generating source (transducers) as well as of the effects of the wave diffraction on the obstacles and surface crackings.

Final remarks

Optical methods of measurement and visualization of the acoustical field render wide of research possibilities in the field of ultrasonic wave propagation in solids and fluids. They may be also employed in the material investigations in particular of the respective surface states. In this case the acoustic wave of the corresponding length plays the part of the detector reacting to the surface discontinuities by a perturbation (due to diffraction) of the symmetry of the wave-front lines observed immediately on the TV monitor.

It is worth emphasizing that the investigations carried out with the help of the above optical methods are nondistructive. Besides they cause no perturbances of the acoustic wave propagation and visualize the real state of the examined elements.

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Применение методов когерентной оптики для исследования акустического поля

Приведены оптические отражательные методы измерения параметров и визуализации акустической поверхностной волны (АПВ). Эффективность метода иллюстрируют результаты измерения параметров АПВ в монокристалле иодата лития со срезом z и распространением x, фазовая скорость $\nu = 2220 \pm 11$ м/с и амплитуда АПВ $\delta = 2{,}60 \pm 0{,}01$ нм. Бегущая акустическая волна была визуализована в двух системах: методом пространственной фильтрации и методом акустической стробоскопии, в результате которой было получено стационарное изображение волновых фронтов.