Proceedings of The Institute of Acoustics

ACOUSTOOPTICS AND ITS PERSPECTIVES IN RESEARCH AND APPLICATIONS

A.S. Śliwiński

Institute of Experimental Physics, University of Gdańsk, Gdańsk, Poland

INTRODUCTION

A fast development of acoustooptics is observed in last years. Many papers have been published and the field of its application continuously increases. Acoustooptics is evidently present at such general acoustical meetings like ICA congresses or Ultrasonics International conferences. Special conferences are organized on the topic. Three International Spring Schools on Acoustooptics and its Applications [1-3] hosted by the University of Gdańsk took place at Wieżyca in 1980, 1983 and 1986. The next is planed in 1989.

Choosing the topic for the Honorary R.W.B. Stephens Lecture to present it to so wide specialized in acoustics audience the author decided to give a short review on the principles of light and sound interaction concidering a few phenomena and some aspects of their practical applications.

At the beginning a historical survey is given refering to many detail papers which may help to learn a bit more, however, the author realizes that the survey is not complete, expecially while relating actual achievements in the field.

Some words and selected examples are presented on the following:

Phenomena taking place in the light and sound (usually ultrasonics) interaction process;

Illustrations of light and ultrasonics interaction phenomena and some applications of holographic interferometry for visualization of sound fields and vibrations of transducers;

Examples of acoustooptical devices;

other applications in selected domains of research and practice.

At the end some trends in further development of acoustooptics are shortly characterized.

HISTORICAL SURVEY

The term acoustooptics[x/] has appeared for about 20 years when due to the invention of lasers a new stimulus in examination of light and sound interaction phenomena initiated further discoveries and many applications in that domain. However, an origin of acoustooptics may be dated on 1932 when two independent experimental papers on ultrasonic light diffraction phenomena by Debye and Sears [4] in USA and Lucas Biquard [5] in France have appeared. The 50th anniversary of that fact was checked off by Mertens [6] during the 12th Congress on Acoustics in Paris in 1983. However, looking back in the history one must find that since the theoretical papers of Brillouin (1922) [7] the ideas on light and elastic waves interaction had existed and were used as a background to stimulate experiments on light scattering by molecular elastic waves (or thermal waves) Brillouin [7] and Mandelsztam [8] (1926), Landsberg and Mandelsztam (1928) [9], Raman and Krishnam [10] (1928) and Gross [11]. Taking that into account one can speak about 65th anniversary of acoustooptics. Moreover, some static elastooptic effects were observed as early as in 1816 (birefringens of a glass plate under bending discovered by Brewster) and phenomenologically formulated in 1890 by Pockels [12]. Such acoustooptical experiments as photographing of sound waves with shadow and schlieren methods were described in 1906 by Toepler [13]. In the evidence of that the history of acoustooptics has more than 170 years. One can go even before "Adam and Eve" as emphesized by Greguss in 1983 [14] when consider sound and light interaction being present at the act of creation of the universe.

However, the date 1932 is significant as the starting point for systematical examinations of light and ultrasonics interaction.

---

x/ The term opto-sonics is also used, however mainly in integrated optics and opto-electronics. The term photo-acoustics is reserved for phenomena of generating sound by light being a base for photoacoustics spectroscopy and will not be discussed in may talk.

Fundamental theoretical as well as experimental papers were next published in 1930-ties [15-18]. Two theories of light diffraction by ultrasound have occured important and they are still useful. The Raman-Nath [15] theory limited to small values of the so called Raman-Nath parameter

$$\zeta = \frac{2\pi\mu L}{\lambda} \qquad (1)$$

depending on the thickness of the ultrasonic layer, L, and the ultrasonic pressure p, which causes proportional values of μ, where μ is the refractive index variation and λ the wavelength of light. Another theory was elaborated by Lucas and Biquard [18]. However, it is valid for larger values of ζ.

The Raman-Nath theory starts from the assumption that the light passing through the ultrasonic beam is only affected in phase, without changing amplitude or trajectory. This assumption is equivalent to solving Maxwell's equations neglecting the term containing the gradient of refraction index, which was also performed by Raman and Nath.

On the other hand, the Lucas-Biquard theory starts from the assumption that change in light amplitude and its trajectory is important and the change in phase can be neglected. They started from the differential equation describing the trajectory of the light beam. Usually the first theory is known as the phase--grating theory and the other as the amplitude grating theory. Both are mutually complementary and they are still very often used for many practical calculations because of their relative simplicity.

More general and more exact theories appeared later and we can mention here Rytov [19], Wagner [20], Kuliasko [21], Leroy [22], Mertens [23], Phariseau [24], Hiedemann [25], Michailov and Shutilov [26], Mayer et al. [27], Hargrove [28], Klein and Cook [29], Breazeale and Hiedemann [30].

Since 1948, Bragg diffraction of light by ultrasound has been considered, (discovered by Bagavanthan and Rao [31]). After that the new parameter, ς, was used to differentiate between the two cases: $\varsigma \ll 1$ (Raman-Nath region) and $\varsigma \gg 1$ (Bragg region):

$$\varsigma = \frac{\lambda^2}{\mu_o \mu \Lambda^2} \tag{2}$$

where Λ is the wavelength of ultrasound, and μ_o the refractive index of the undisturbed medium.

It should be mentioned that there exist few parameters used as criteria to distinguish between the Raman-Nath and Bragg types of diffraction among which two are the most popular: ς (as difined above) and

$$Q = \frac{2\pi \lambda L}{\mu \Lambda^2} \tag{3}$$

In both cases the criterion is $\varsigma < 1$ or $Q < 1$ for the Raman-Nath diffraction and $\varsigma > 1$ or $Q > 1$ for the Bragg diffraction. In the papers of Klein and Cook [29], Hiedemann and Cook [32] and Mejias [33] the dependence on ς for diffraction of light by an ultrasonic wave have been considered.

There is not a uniform opinion in the literature which of the parameters is better for the criterion [34,35]. It is easy to show that the mutual relation between ζ, ς and Q is $Q = \zeta \cdot \varsigma$. The relation between ς and Q, when the last one is used as the criterion has been discussed in [34,35]. It was shown there by the dependence of ζ against Q that a wide range of the values of Q corresponds to the value of $\varsigma = 1$. The range of the parameters ς and Q in the vicinity of 1, which was distingnished in [29] as the intermediate region, is very interesting from a physical point of view because in this range one has the Raman--Nath and the Bragg types of diffraction mixed together [33,36]. There are papers trying to construct general theories of diffraction of light by ultrasound [37,38] where both types of diffraction are described as particular cases using the criteria just mentioned.

Independently of the main interest during the last 60 years in diffraction of light by a single ultrasonic beam some papers have been published on more sophisticated cases of the phenomenon, such as diffraction of light by an amplitude-modulated ultrasonic beam, by two superposed ultrasonic beams and by two adjacent ultrasonic beams.

Some experiments on ultrasonic light diffraction by two superposed beams were performed by Bergmann and Fues [39] and Govinda Rao [40]. Theoretical explanations were also given by Bergmann and Fues and by Nagendra Nath [41], Ramachandra Rao [42] and Nagabhushana Rao [43]. The problem was developed in the 1950's by Murthy [44], Zankel and Hiedemann [45] and Mertens [46].

Experiments on the diffraction of light by an amplitude-modulated ultrasonic beam were first performed by Pancholy and Parthasarathy [47]. First theories on this phenomenon were given by Aggarwal, Pancholy and Parthasarathy [48,49]. Later, they were developed by Phariseau [50], Kuliasko, Mertens and Leroy [21,22] and lastly by Mertens [51,52]. Diffraction of light by standing ultrasonic waves was considered by Kuliasko, Mertens, Leroy and Plancke-Schuyten [53,54,55].

Since 1960 the problem of diffraction of light by two adjacent ultrasonic beams has been considered by Mertens [56], Hargrove, Hiedemann, Mertens [57] and Leroy [58]. The problem is not only interesting for two adjacent beams with the same frequency, but also for frequencies in the ratio 1:n, where n is integer. The special cases of 1:1 and 1:2 have been theoretically treated as well for $\varrho < 1$ and $\varrho > 1$ by Leroy [58]. Later on, these theoretical results have been verified by Kwiek and Śliwiński [59] for $\varrho < 1$. More detailed discussions of the problem and experimental results have shown very interesting behaviour of the output light beams of the +1 and -1 orders [60]. These results stimulated more precise numerical calculations as well as further experiments [61-66,36] looking for dependence on ζ and the phase-difference δ between the two adjacent ultrasonic beams. It was also possible to develop a more general theory

of the phenomenon for $\varrho < 1$ and $\varrho > 1$ by Leroy and Blomme [67] and Calligaris, Ciutti and Gabrielli [68-70], Patorski [71].
Many experimental as well as theoretical papers on the interaction of light and sound have been published during the last 60 years (Berry [72] , Born and Wolf [73] but a particular interest has become evident in the last decade with the development of lasers, and many applications of acousto-optic devices such as deflectors and modulators have been appeared.
Also other devices used in integrated optics have been invented (Tamir [74], Sapriel [75], Mason [76], Hunsperger [77] Balakshii et al. [78] , Berg [79,80], Chang [81]).
The above mentioned literature is related mainly to ultrasonic light diffraction phenomena. However, during last 20 years, since coherent sources of light have appeared, optical schlieren [82,83] interferometric methods have been evidently developed, including holography, and applied to ultrasonic field and vibrations visualization [84-97].
Acoustooptical methods have been applied and developed in examination of molecular systems [98-111]. Great achievements in last 2 decades have been observed in light interaction with surface acoustic waves, particularly in the integrated optics [74--81,112-116].
A special interest is paid to acoustooptical interactions in anisotropic media [75,78,38,117-121] as solids, liquid crystals, some organic- and bio-liquids [103].
In many nonlinear problems acoustooptics is used [26-30,100,101, 122-127] for demonstrating nonlinear phenomena and for determination of nonlinear parameters.
Recently, the problem of light and ultrasonic pulses interaction is intensively examined [128-135].
Since optical waveguides were invented and applied in integrated optics [74,77] there have appeared many possibilities to construct and develop acoustooptical sensors [136-140] which occured to be very effective and sensitive.

PHENOMENA OF LIGHT AND ULTRASONICS INTERACTION

An isotropic medium

General mechanism of interaction. Let us consider (Fig. 1) crossing of light and ultrasonic beams of thicknesses d and L, respectively at an angle θ in an isotropic medium. Interacting (in hatched area) with ultrasound the light yields scattering and diffraction (this part of scattering which is a result of interference of scattered rays) due to variations of light refractive index and its gradient induced by ultrasound. The geometrical result of interaction of light with ultrasound is variation of direction of scattered rays i.e. their deflection respect to the incident light. For a sinusoidal ultrasonic wave of the wave-length Λ in a case when the width of light beam d is greater than Λ $(d > \Lambda)$, i.e. when the light beam contains more than one US wavelength, a regular diffraction process occur, however when $d < \Lambda$ only deflection takes place. The situation is presented more precisely in the Fig. 2, where $\theta = 0$ and the light beam is formed in the optical system. From the slit S the light goes through the objective O_1 and interacts with the ultrasonic wave (US). After scattering and diffracting (in the Figure only the 0 and ±1 orders of diffracted rays are drawn for simplicity) the light is focused on a small disk[x] (of an area of the focus for non scattered rays). Because of the presence of the disk, only scattered and diffracted rays may pass by the disk. Only those rays form schlieren images. As it is seen from the auxiliary construction in the Figure 2 every order (+1) and (-1) forms its own image. First is closer (I - is called a near schlieren image of the 1st order and the second is farther (II - is called a far schlieren image of the 1st order).

In a case of a knife deadlight one gets only one image with +1

---

x/ In traditional schlieren arrangements instead of a disk a knife is used and only the half area of the focus is blanked off.

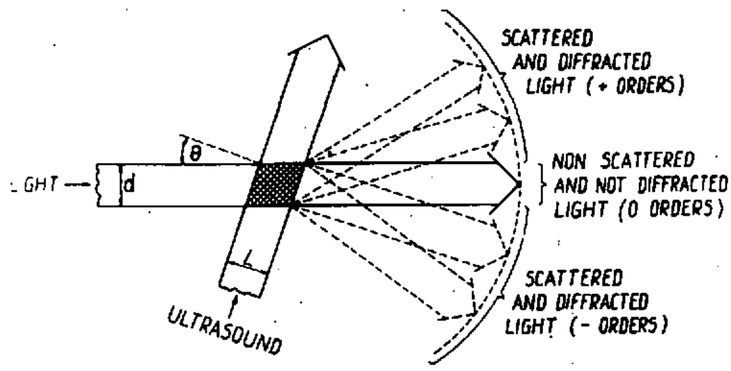

SCATTERED
AND DIFFRACTED
LIGHT (+ ORDERS)
θ
d
NON SCATTERED
AND NOT DIFFRACTED
LIGHT (0 ORDERS)
L
SCATTERED
AND DIFFRACTED
LIGHT (- ORDERS)
ULTRASOUND

Fig. 1

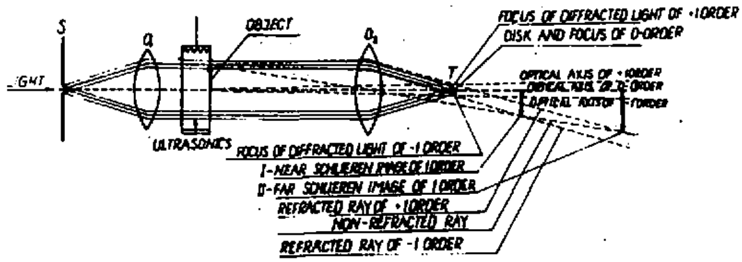

S
OBJECT
FOCUS OF DIFFRACTED LIGHT OF +1ORDER
DISK AND FOCUS OF 0-ORDER
T
OPTICAL AXIS OF +1ORDER
ULTRASONICS
FOCUS OF DIFFRACTED LIGHT OF -1 ORDER
I-NEAR SCHLIEREN IMAGE OF 1ORDER
II-FAR SCHLIEREN IMAGE OF 1 ORDER
REFRACTED RAY OF +1ORDER
NON-REFRACTED RAY
REFRACTED RAY OF -1 ORDER

Fig. 2

or -1 order rays depending on whether the upper or lower side is blanked off. Our object is an ultrasonic field. In a case of standing wave the image of the field is straight visible. In a case of progressing wave a momentary (exposure duration $< 10^{-7}$s) or stroboscopic flashing must be used.

Diffraction of light on a single US wave

If one puts a screen at the focus plane instead of the disk (Fig. 3) the diffraction pattern of light diffracted by the ultrasonic wave would be visible on the screen. Because of the periodic structure of the US wave with a period of Λ (ultrasonic wavelength) the diffraction process occurs as similar to those taking place on an optical diffracting grating of the grating constant equal Λ . Usually, for magnification the objective O (Fig. 3) is situated straight behind the vessel with ultrasonics. The diffraction pattern (diffraction spectrum) observed on the screen at the focus distance A is schematically presented on the right side of the picture paralelly with a light intensity distribution in diffraction orders.

The distribution for a case when the light beam is perpendicular to the ultrasonic one is symmetric what does not take place when $\theta \neq 0$ (Figs 1 and 4). As we already mentioned, for $d > \Lambda$, a regular diffraction of light occur, however in general case depending on physical conditions two kinds of diffraction may appear: Raman-Nath (Fig. 4a) or Bragg (Fig. 4b). The criteria defined in (2) or (3) are equivalent to the following conditions relating to the description of the Fig. 1:

$\lambda L < \Lambda^2$ for Raman-Nath diffraction, what corresponds to

$$\rho < 1 \text{ or } Q < 1$$

and $\lambda L > \Lambda^2$ for Bragg diffraction, what corresponds to (4)

$$\rho > 1 \text{ or } Q > 1.$$

The distribution of light intensity in the diffraction pattern strongly and in nonlinear way [15] depends on an ultrasonic power or more exactly on the Raman-Nath parameter ζ (1) being proportional to acoustic pressure and width of the ultrasonic

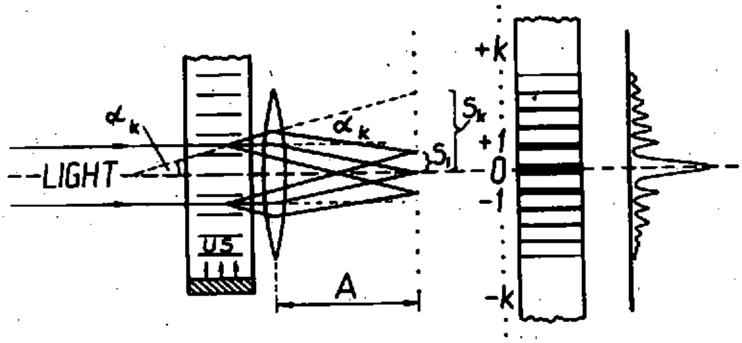

LIGHT
US
A
+k
+1
0
-1
-k

Fig. 3

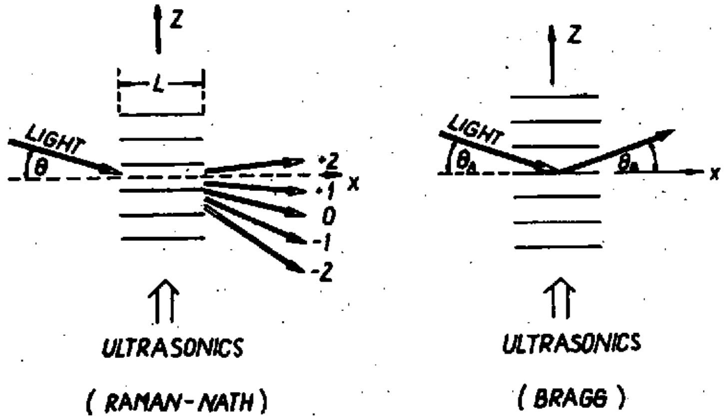

Z
L
LIGHT
θ
+2
+1
0
-1
-2
x
ULTRASONICS
(RAMAN-NATH)
Z
LIGHT
x
ULTRASONICS
(BRAGG)

Fig. 4

beam. For a sinusoidal ultrasonic wave the variation of light refractive index is given by the formula

$$\Delta n = \mu \sin 2\pi\left(Nt - \frac{x}{\Lambda}\right) \tag{5}$$

where μ - amplitude of the variation Δn, N - frequency,
x - direction of propagation of ultrasonics.

Then, according to Raman-Nath theory [15] the amplitude distribution in output plane (behind the US wave - Fig. 3) is described by the expression

$$C\sum_{k=-\infty}^{+\infty} J_k(\zeta)\, e^{i\left[2\pi(\nu+kN)t - \frac{2\pi}{\Lambda}\left(z + k\frac{\lambda}{\Lambda}x\right)\right]} \tag{6}$$

where C - amplitude of the incidenting light wave of frequency ν,
J_k - Bessel function of the first kind of k order,
z - direction of the propagation of light,

and the light intensity in a given diffraction order k (k is integer) is proportional to the square of the Bessel function [15,72,73] of the argument ζ :

$$I_k \sim J^2(\zeta) \tag{7}$$

One can see from (6) that the light diffracted rays are deflected of different angles, where for a given order k

$$tg\, \alpha_k = k\frac{\lambda}{\Lambda} \tag{8}$$

Due to the Doppler effect the diffracted rays are modulated in phase with the US frequency N and in a given order k the light frequency is

$$\nu_k = \nu \pm kN \tag{9}$$

The condition for the Bragg diffraction (Fig. 4b) can be determined as the following relation between incidenting light vector $\vec{k}$, ultrasonic wave vector $\vec{K}$ and the diffracted light vector $\vec{k}'$

$$\vec{k}' = \vec{k} \pm \vec{K} \tag{10}$$

The angle α_k may be measured experimentally as it is shown in the Fig. 3. For small angles

$$\alpha_k \approx tg\,\alpha_k \approx \sin\alpha_k = \frac{S_k}{A} \qquad (11)$$

whence

$$k\frac{\lambda}{\Lambda} = \frac{S_k}{A} \quad , \qquad (12)$$

where S_k - distance of the k-th order diffraction fringe from the 0 optical axis

A - focus distance of the objective.

From (12) one gets the wave-length of the ultrasonic wave

$$\Lambda = \frac{k\lambda A}{S_k} \qquad (13)$$

It is commonly known [72,98,99] that the formula (13) enables to determine the velocity of sound $c = \Lambda N$, when the frequency N of the ultrasonic wave and the wavelength of light λ are known. Measuring of the light intensity I_k in a given order allows to determine the Raman-Nath parameter ζ [72,98,99,145] and consequently to determine acoustic pressure or power of the ultrasonic wave as well as to measure the absorption coefficient of the ultrasonic wave.

Optical holography and sound field visualization

The basic phenomena described shortly here are important for further considerations when optical holography is applied [84-97] for sound and vibrations visualization. The Fig. 5 represents a scheme of constructing process of an optical hologram of an ultrasonic wave. Comparing the situation of the object beam Σ_p in this Figure with the scheme analyzed in the Figs 2 and 3 one can see that the beam is carrying total information about US wave and light interaction (amplitude and phase distribution). As a result of interference of the object beam Σ_p and the reference beam Σ_o on the plane H the hologram is constructed and recorded with a photo-plate.

The Fig. 6 represents a scheme of reconstruction process of the object (US wave) from the hologram. In the following the

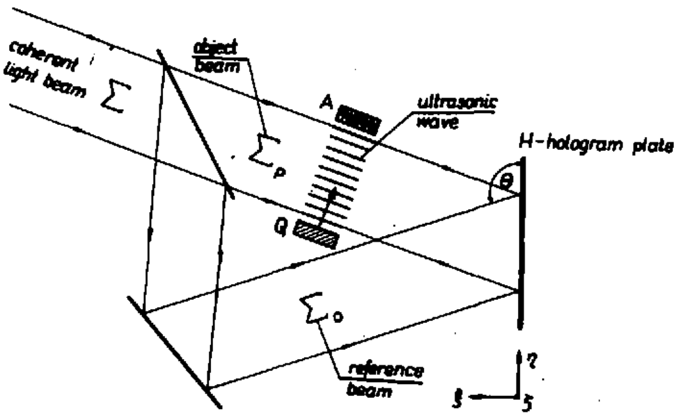

coherent light beam Σ
object beam
Σp
A
ultrasonic wave
H-hologram plate
θ
Q
Σo
reference beam
η
ξ
ζ

Fig. 5

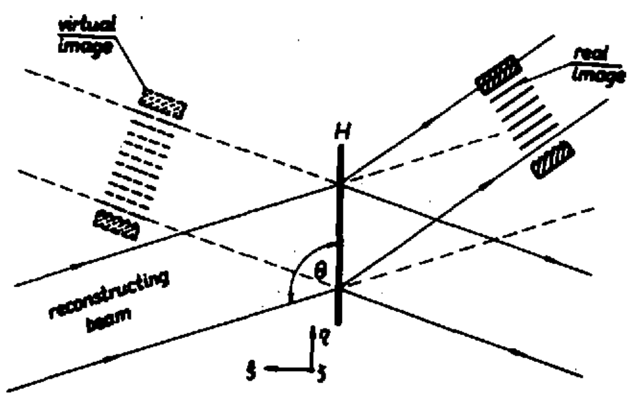

virtual image
real image
H
θ
reconstructing beam
η
ξ
ζ

Fig. 6

acousto-optic holography procedure just described will be examplified.

Diffraction of light by two adjacent beams

As the next step let us consider the diffraction of light by two adjacent ultrasonic beams. The geometrical situation is schematically presented in the Fig. 7, with that the frequency of the second ultrasonic beam is the k-th harmonic of the first one. Such harmonic relations are more interesting than a general case. In the figure μ_1 and μ_k are amplitudes of variations of light refractive indices for the first (fundamental) and the second (k-th harmonic, respectively. ν - frequency of the first beam $k\nu$ - frequency of the second beam, k is an integer, δ - the phase shift between two US beams, L_1, L_2 - thicknesses of the beams, respectively, z - direction of the propagation of light. It has been shown [56-58] that the light distribution at the output of the system depends on the phase shift δ. The general formula (when $\rho \ll 1$) for the distribution of light amplitudes in diffraction orders (r) after passing through the two adjacent US beams progressing in the same direction is given by

$$\Psi_r = \sum_{q=-\infty}^{+\infty} J_{r-kq}\left(\zeta-\zeta_1\right)\cdot J_q\left[\alpha_k\left(\zeta-\zeta_1\right)\right]\exp\left(-iq\delta\right) \tag{14}$$

where r, k, q - natural numbers, $\zeta = \frac{2\pi\mu_1 z}{\lambda}$,

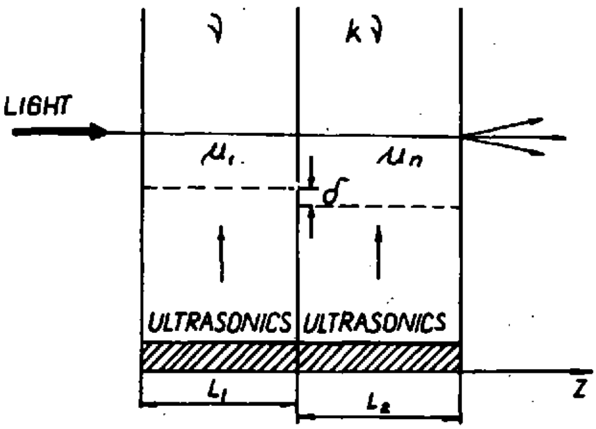
$\zeta_1 = \frac{2\pi\mu_1 L_1}{\lambda}$, $\zeta_2 = \alpha_k \zeta_1 \frac{L_1}{L_2}$, $\alpha_k = \frac{\mu_k}{\mu_1}$, λ - wavelength of light

For light intensity one gets from (14)

$$I_r\left(\zeta\right) = \Psi_r \cdot \Psi_r^* = \sum_{q=-\infty}^{+\infty} I_{rq}\left(\zeta\right)\cos q\delta \tag{15}$$

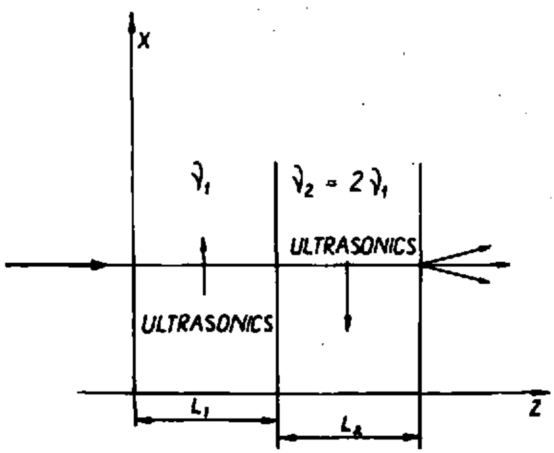
The formula (15) may be approximated when $\zeta_1 < 1$ by the trigonometrical functions [61] to the expression

$$I_{\pm r}\left(\zeta\right) = I_r^{\circ}\left[1 \pm \left(-1\right)^r \cos\delta \sin \alpha_{kr}\zeta_1\right] \tag{16}$$



LIGHT
ULTRASONICS
ULTRASONICS
Z

Fig. 7



X
ULTRASONICS
ULTRASONICS
Z

Fig. 8

where I_r^o - intensities after passing the first beam.
The cosinusoidal dependence on δ according to (16) and (15) was experimentally verified in our laboratory [59-62] and many experiments and calculations were performed [63-66] for different values of α_k, ζ_1 and ζ_2 in several diffraction orders (odd and even) against δ for different ratios of frequencies of ultrasonic beams. Also, the case of two adjacent beams being opposite in direction of propagation was examined [142] for frequency ratio of 1:2 (Fig. 8). The phenomenon in that case differs from the one of diffraction by adjacent beams propagating in the same direction Fig. 7 , namely, light diffraction intensity distributions for opposite beams are modulated in time according to the formula

$$I_r(\zeta,t)=\sum_{q=-\infty}^{+\infty} I_{rq}(\zeta)\cos q\left(2k\Omega t+\delta\right), \quad (17)$$

(where Ω - angular ultrasonic frequency of the first beam) while for beams propagating in the same direction are not dependent on time (see form. (15)). Also the role of phase shift δ is different in both cases. In (17) δ only shifts the time scale, while in (15) or (16) one can get modulation against δ. Later on examples will be presented.

<u>An anisotropic medium</u>

<u>Acoustooptical interaction in crystals and liquid crystals.</u>
Relationship determining acoustooptical interaction in anisotropic medium must take into account the tensor character of quantities describing their elastic and optical properties and the coupling existing among them [117-122,75-78]. Such relations have been phenomenologically formulated by Pockels [12] in his theory of elastooptics. However, his theory had an essential drop till 1970 when it has been extended by Nelson and Lax [117] who introduced the coupling between strain and rotation of a medium. The coupling is responsible for so called roto-optic effect when applied shear deformations in birefringent crystals (or

liquid crystals). That has had important consequences for acoustooptics [37,120]. Acoustooptical phenomena are more complex in anisotropic medium because the acoustic variations of stresses and deformations of a medium, (which induce changes in optical refractive index distribution) depend on the symmetry of the medium (i.e. direction of propagation respect to the cristal axis - birefringent effects appear) and on the states of polarization both of light as well as of acoustical wave.
The diffraction of light by ultrasonics in anisotropic transparent media has been described in many papers and monographies [75,76,117], however mainly taking into account the Bragg diffraction. The general approach solving the problem both in Raman-Nath as well as in Bragg cases were elaborated by Parigin and Chirkov [37,78]. The theory among others allows to determine amplitudes and intensity distributions of diffracted beams as well as diffraction angles in a birefringent medium.

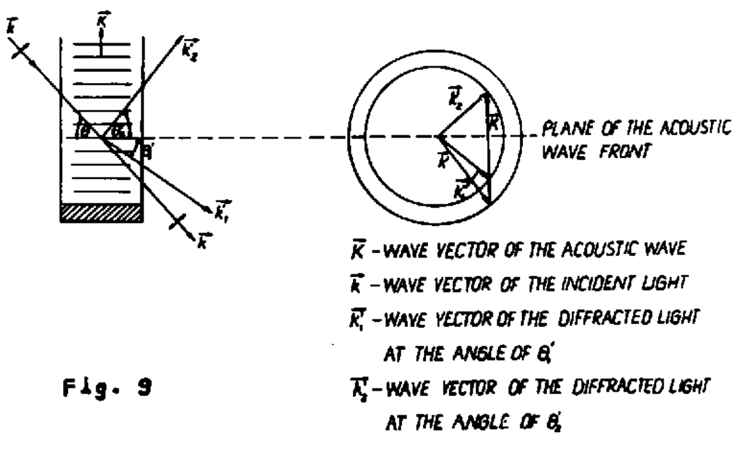


Fig. 9

The Fig. 9 represents a scheme of light diffraction by an ultrasonic wave in a birefringent medium at a given angle of incident. Directions of electric vectors vibrations states of polarization are marked by arrays (at the plane of the figure) and dots (at the plane perpendicular to the figure).

Depending on the mutual relations between ultrasonic frequences, angle of incidence respect to the optical axis and state of polarization many special cases of anisotropic diffraction may be realized [75,76,117].

The angles of diffraction are

$$\theta_B = \arcsin\left\{\frac{1}{2n_o}\left[\frac{\lambda_o}{\Lambda} + \frac{\Lambda(n_o^2 - n_1^2)}{\lambda_o}\right]\right\}, \qquad (18)$$

$$\theta' = \arcsin\left\{\frac{1}{2n_1}\left[\frac{\lambda_o}{\Lambda} - \frac{\Lambda(n_o^2 - n_1^2)}{\lambda_o}\right]\right\} \qquad (19)$$

where n_o - ordinary refractive index corresponding, to the incidenting light of the wavelength λ_o,

n_1 - extraordinary refractive index corresponding to the diffracted light,

θ' - diffraction angle,

θ_B - diffraction Bragg angle.

Anisotropic difffaction is a diffraction with changing polarization state. Conditions for diffraction of light of different states of polarization by an ultrasonic wave can be satisfied only for selectively determined angles depending on the fact whether the state of polarization is conserved or not. Two possible diffraction angles $\theta'_{1/2}$ (Fig. 9) correspond to the required condition.

Diffraction of light by surface acoustic waves (SAW)

The mechanism of light interaction with SAW is described in the Fig. 10. The SAWs are generated by the interdigital transducer on the surface of a substrate and interacts with a light beam. Usually the light wavefront is several times larger than the SAW wavelength, so that real diffraction occurs rather than a time dependent deviation of the energing light beam. The interaction geometry shown in the Fig. 10 corresponds to a case of tranparent substrate. The diffraction pattern appears in reflected as well as in transmited light. Generally three possible geometries

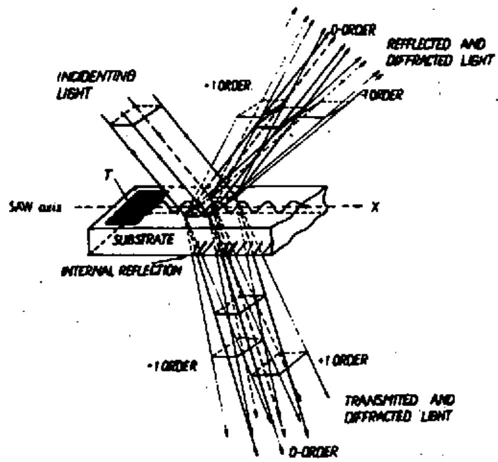

0-ORDER
REFLECTED AND
DIFFRACTED LIGHT
INCIDENTING
LIGHT
+1 ORDER
-1 ORDER
T
SAW axis
X
SUBSTRATE
INTERNAL REFLECTION
-1 ORDER
+1 ORDER
TRANSMITTED AND
DIFFRACTED LIGHT
0-ORDER

Fig. 10

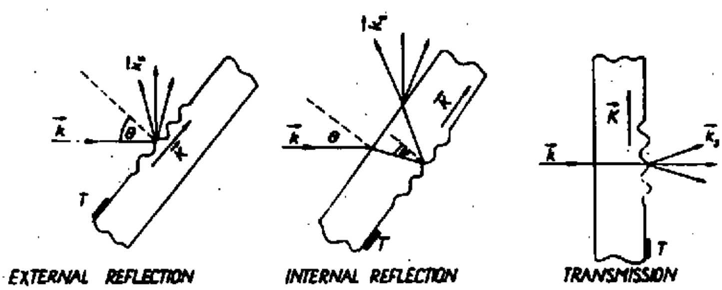

EXTERNAL REFLECTION
INTERNAL REFLECTION
TRANSMISSION

Fig. 11

are considered (Fig. 11): external reflection, internal reflection and transmission. All vectors of the incident $\vec{k}$ and diffracted $\vec{k}_s$ light as well as SAW $\vec{K}$ lie on the same plane normal to the propagation surface and satisfy the momentum conservation law

$$\vec{k}_s = \vec{k} \pm \vec{K} \tag{20}$$

There exist some theories describing this kind of light and SAW interaction and it is possible to describe light intensity in diffraction orders taking into account two components of deformation i.e. surface corrugation and internal deformation below the surface (112-115). For external reflection a diffraction pattern behaves very much like a Raman-Nath pattern for bulk US waves and the light intensity distribution is given by [27] (compare (7)):

$$I_{\pm k} = J_k(w) \tag{21}$$

where now $w = 2|\vec{k}|\, a \cos\theta$, a being an amplitude of surface corrugation.

ILLUSTRATIONS OF LIGHT AND ULTRASONICS INTERACTION PHENOMENA

Schlieren technique

It was shown above (Fig. 2) how the schlieren images are formed. The schlieren technique is rather common for sound visualization [13,39,82,83]. Here, as an example of that technique two photographs presented in Figs 12 and 13[x/] are very interesting cases of sound radiation field evolution just after switching on an ultrasonic transducer, (Fig. 12) and just after the wave front is approaching a slit and forming the diffracted and reflected interference field (Fig. 13). The frequency of the wave propagating in water was 800 kHz.

Diffraction of light by ultrasonics

The Fig. 14 represents spectra of light diffraction orders

---

x/ The pictures were made by Dr R. Reibold in his lab in Braunschweig and are presented here thanks to the courtesy of him [82]

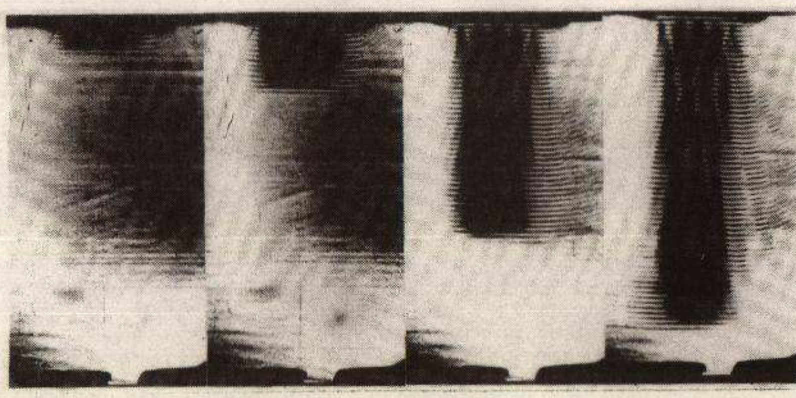


Fig. 12 after [82]

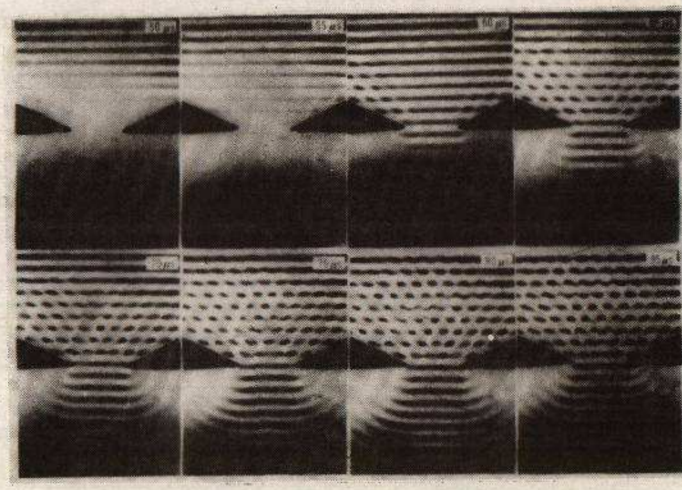


Fig. 13 after [82]

obtained in an experiment:

a) - without ultrasonics,

b) - ±1 orders for a single ultrasonic beam of frequency ν_1 = 800 kHz,

c) - ±1 orders for a single ultrasonic beam of frequency $\nu_2 = 2\nu_1$ = 1600 kHz,

d) - with both ultrasonic beams of ν_1 and $2\nu_1$ operating adjacently for see 14

$$\alpha_2 = \frac{\mu_2}{\mu_1} = 0.3 \ ; \ \zeta_1 = 0.54 \ , \ \delta = 0 \ , \ L_1 = L_2 = 24 \text{ mm}$$

As an example in the Fig. 15 two original [60] recordings of light intensity in +1 order (Fig. 14d) I_{+1} against δ for two adjacent progressing in the same direction US beams are presented. The record (Fig. 15a) is for $\zeta_1 < 1.5$ when cosinusoidal dependence (16), while (15b) is for $\zeta_1 > 1.5$ when the trigonometrical approximation is not valid and the formula (15) describes the dependence [60,64]. The additional maximum (μ_4) in the Fig. 15b for $\delta = \pi$ may be used to measure [60] the nonlinear distorsion of the second US-beam which is responsible for the maximum.

The Fig. 16 represents an example of time modulation of the light intensity in 0,+1 and +2 diffraction orders for the case of two opposite in direction US beams (of frequencies 0.8 and 1.6 MHz) against $4\Omega t$ [142]. The drawings (a) represents results of numerical calculations according (17) and oscilograms (b) records of optical signals from the photomultiplier for the same Raman-Nath parameters ζ_1 = 1.45 and ζ_2 = 1.5.

Optical holograms of ultrasonic fields and transducers vibrations

The Fig. 17 explains a scheme of the arrangement used in our lab [89,90] for recordings simultaneous holograms (see Figs 5 and 6) of ultrasonic fields and distributions of vibrations on the surface of the transducers radiating these fields. The holograms H_u and H_v correspond to the US field and transducer surface vibrations, respectively, M - denote modulators of light of the

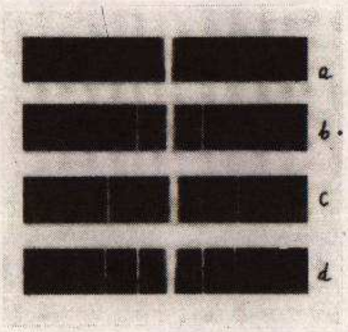


Fig. 14 after [60]

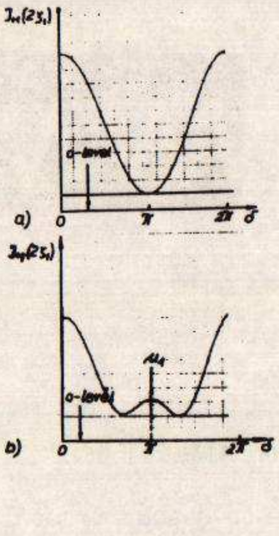
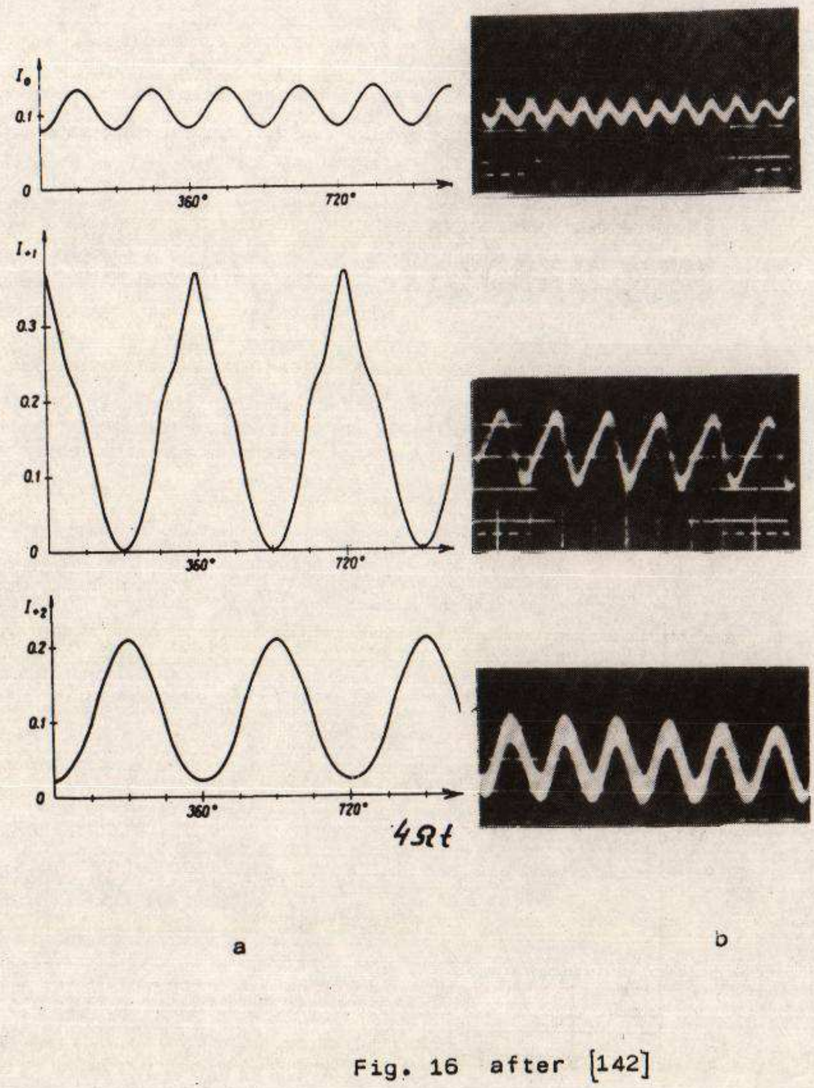


Fig. 15 after [60]



a b

Fig. 16 after [142]

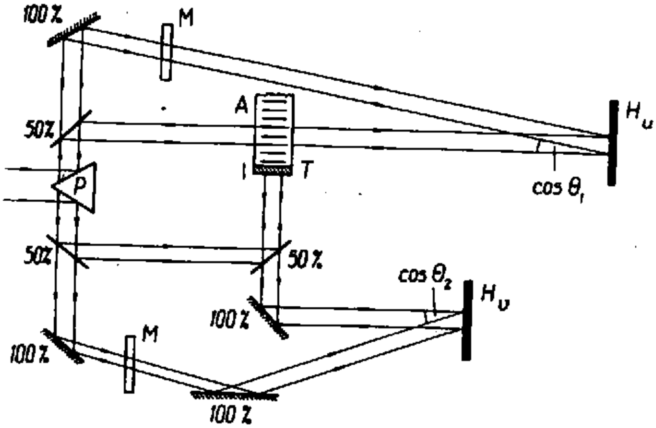


Fig. 17

reference beams. L - stands for light (coherent), T for transducer, A - absorber (to diminish reflections) and P - prism, respectively.

Many examinations were performed and all interferometric holographic methods i.e. averaged in time, two exposures, stroboscopic and real time methods, were proofed [87-97]; previously adapting the normal optical holography (without reference beam modulation) and later on using the reference beams modulated in phase or in amplitude. The progress of the matter is, that in the case of unmodulated reference beam the light intensity distribution in the image reconstructed from a hologram is proportional to the square of the Bessel function of 0 - order i.e. to $J_0^2(\Delta)$ where the argument Δ in the case when an object of the holography is an ultrasonic wave is the Raman-Nath parameter (1) $\Delta \equiv \zeta = \frac{2\pi\mu L}{\lambda}$ and in the case of a vibrating transducer $\Delta = \frac{4\pi d}{\lambda}$; where λ - wave length of light, μ - amplitude of variations of refractive index caused by acoustic pressure, L - width of the US wave, d - vibrational amplitude of an element of the surface of the transducer; Instead, in the case of adequatly modulated reference beam, one can get the light intensity distribution in a reconstructed image as proportional to the square of the Bessel function of higher orders $J_k^2(\Delta)$, where $k \geqslant 1,2,3...$ It happens so, because in the process of hologram reconstruction of the object vibrating with the frequency Ω, the object light beam of the frequency ω after passing through the object (US beam) or after scattering on it (vibrating surface of a transducer) contains components of higher orders of frequencies $\omega \pm k\Omega$ (see (9) - now $\omega = 2\pi\nu$ and $\Omega = 2\pi N$). As a result of interference of the object beam and the reference beam modulated in phase with the frequency of one of those components, there appear the light intensity distribution proportional to the square of the Bessel function of the order which corresponds to this selected component. Analysis of the phenomena has shown [88,90-92,95] that the optimal conditions for sensitivity and contrast took place for $k = 1$. In that case when the light intensity distribution was described by $J_1^2(\Delta)$, the contrast of the image respect to the background is reciprocal to that in the case $J_0^2(\Delta)$ (Fig. 18) i.e. that one observes brightening on the dark background instead of decreasing of the image brightness on the light background. In practice it means an increase of sensitivity for visualization of vibrating objects of more that one order of magnitude.

In the case of the cosinusoidal amplitude modulation of the reference beam with the frequency of vibrating object the light intensity distribution in the reconstructed from the hologram image of an US-wave is proportional to the expression [91]: $J_1^2\left(\frac{2\pi\mu L}{\lambda}\right)\sin^2\left(\frac{2\pi x}{\lambda}\right)$, where X - coordinate in the plane of the hologram.

The Fig. 19 represents a photograph of the holographic image of the US wave of 1.5 MHz radiated by the BAT transducer to the water reconstructed from the hologram (obtained by P. Kwiek [91]) using the amplitude modulation reference beam. One can easily noticed that the wave fronts and other details of the directivity characteristic of the US-field are very distinct in that image. One should remember that the real image reconstructed from the

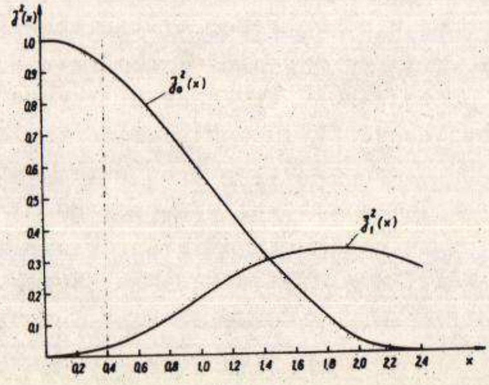


Fig. 18

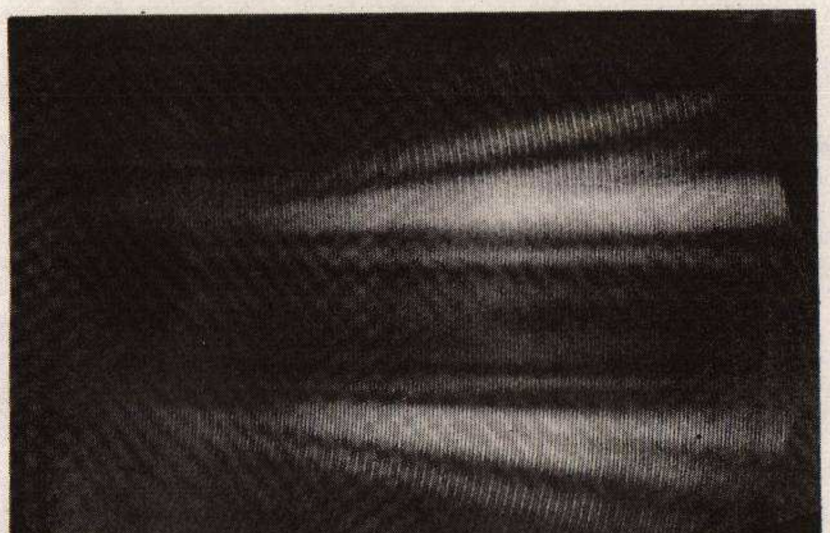


Fig. 19 after [91]

hologram has a spacial structure and may be viewed at different crosssections at different angles. The sound field in such image can be scaned with a point photodetector [89] and the acoustic pressure distribution at a given range of the beam may be determined. The next Fig. 20 is an example of the case when the image has been viewed and photographed at three different cross-sections at different angles [85]. The object was the ultrasonic wave of frequency 0.5 MHz propagating from water to acetic acid through an organic foil. The special vessel made of poliethylene foil filled with water is dipped in a larger vessel containing acetic acid. One can notice a differences in the wavelength in both media because different sound velocities in both media. Another Fig. 21 represents two photographs from the reconstructed images (obtained by I. Wojciechowska [90]) of vibrational amplitudes distribution on the back (see Fig. 17) surface of the BAT ultrasonic transducer radiating to the water. The hologram was obtained with the reference beam modulated in phase with the frequency $\omega + \Omega$ (see above). The transducer of the diameter 30 mm and the thickness 3.75 mm was supplied with the voltage 30 V rms. The photos represents vibrations on the surface of radiating transducer at the resonance frequency 508 kHz (a) and retuned below resonance at 488 kHz (b) and above resonance at 528 kHz (c). In the Fig. 22 one can see the same transducer (Fig.21a) vibrating after clamped with the fixing ring around the periphery.

Examination of the reconstructed images, scaning them with the micro system coupled with the photomultipler [90] and a computer, gives a possibility to obtain a map of vibrational amplitudes throughout the transducer surface (Fig. 23 - only half of the surface is presented).

The holographic interferometry applied to examination of piezoelectric US-transducers allowed to record holograms of radiating characteristics (field distributions) and vibrational amplitudes on transducer surfaces with the accuracy of 10^{-7} Pa for acoustic

Fig. 20 after [89]

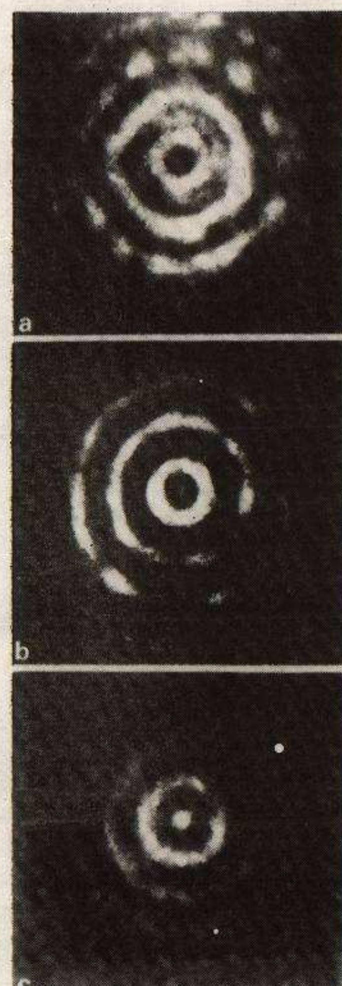


Fig. 21 after [90]

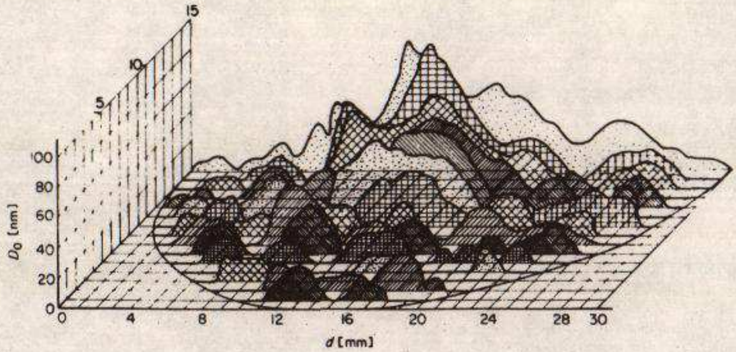


Fig. 22 after [90]

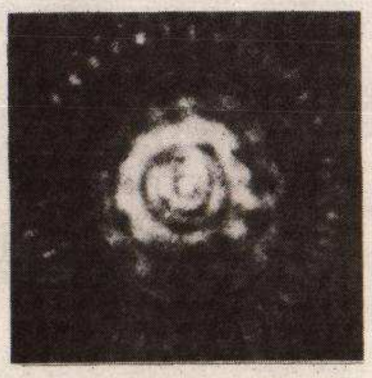


Fig. 23 after [90]

pressure and 10^{-9} m for displacements [88-93,97]. The methods are very useful to find very small irregularities in radiating characteristics as well as small innomogeneous in vibration distributions which contribute to those irregularities.

Recently, one can observe a fascinating development of the fast and super-fast holographic interferometry coupled with computer data processing to study transient and rapid processes in their time evolution. As an example one can see in the Fig. 24 the results of acoustic pressure pulse profile change during propagation at two distances 6 mm and 75 mm depart from the transducer . The duration of the pulse was 3 μs at 6 mm and the nominal frequency about 2 MHz [134].

It is worse to mention another example of the super-fast holographic photography (up to 10^6 frames per second) applied for examination of dynamical processes of cavitation bubbles by Lauterborn and Hentschel [143].

The Fig. 25 represents the evolution of cavitation bubbles as well as shock waves generated at the collapsing process of bubbles.

EXAMPLES OF ACOUSTOOPTICAL DEVICES

It might be possible to speak about varions devices related to principles of all phenomena we have just described, however such a list would be very long, indeed. So, only few examples will be talked ower, here the more so, that the devices are considered in many books and papers [74-81,144]. Essential components of acoustooptical systems used for signal processing are deflectors and modulators based upon the Raman-Nath (Fig. 4a) or Bragg (Fig. 4b) cells. Such cells may be constructed using both isotropic or anisotropic media. Typical materials are water or fused silica (isotropic) and crystals (anisotropic) like lithium niobate - $LiNbO_3$, tellurium dioxide - TeO_2 and others or liquid crystals. Applying such cells one can transform electric signals through US - transducers radiating acoustical wave into optical ones in the a.o. interacting process. Depending on the material

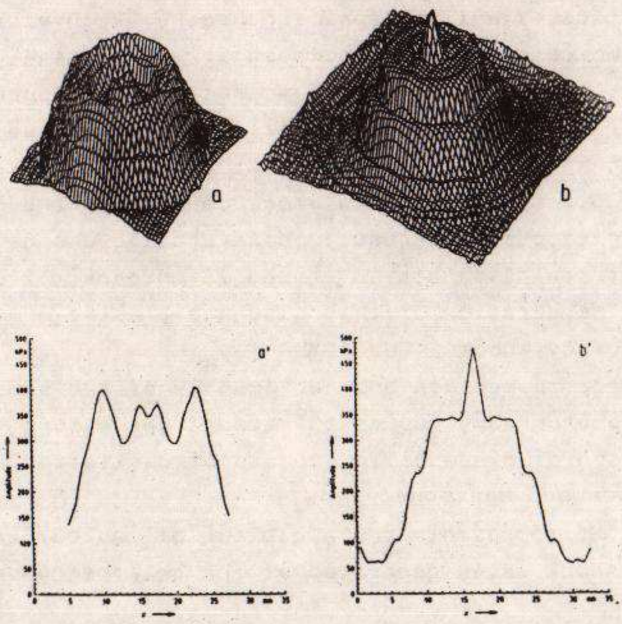


Fig. 24 after [104]

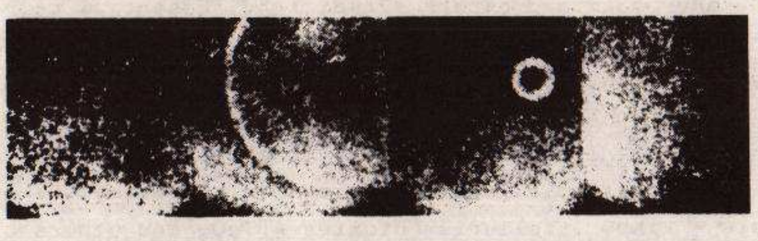


Fig. 25 after [143]

used the acoustooptical efficiency may be smaller or greater. In the case of a Bragg cell for an incident angle $\theta = \theta_B$, where the Bragg angle $\theta_B = \frac{\lambda}{2\Lambda}$ and for sufficiently large thickness of an US - beam, the diffracted light beam will be concentrated in +1 or -1 order. The light intensity of the beam reflected at the Bragg angle is given by the formula [79,144]:

$$I_D = I_0 \sin^2 L \sqrt{2 M_2 P_a} \qquad (22)$$

where M_2 is a material figure of merit and P_a - acoustic power density.

For small acoustic powers ($\zeta < 1$ - see (1)) the intensity of diffracted light is proportional to the input signal. If the a.o. cell is driven by an input signal (may be complex), then the diffracted light would contain total information about amplitudes, frequencies and phases of that signal (related to the portion being in any given instant illuminated in the cell and delayed respect to the electric signal at the transducer of the time required for US - wave to travel to the interaction region).

The bandwidth of the a.o. signal is limited as by the bandwith of the US - delay line as well as by the efficiency of interaction process (e.g. a cell length limited by attenuation of ultrasound etc.). The time - bandwidth product determined by these limitations is an important performance measure for a.o. signal processors. An instant bandwidth and a long time delay of a.o. devices predestinate them for real-time signal processing. The most important operation are: Fourier transform, correlation convolution and deconvolution.

There are two basic architectures of acoustooptic signal processors: the space - integrating type and the time - integrating type [79]. In the first type the spatially modulated optical beam in the a.o. cell may go through certain operations such as multiplication with a reference beam and then be spatially integrated into a detector. The final integration is the diffraction integral and the output data is a function of time. On the other hand in the second type the integration operation is performed in time domain and the output data is expressed as a function of the spatial variable. Many devices of both types were elaborated [77-81]. Examples of these two types of a.o. signal processors are presented in the next following figures.

In the Fig. 26 an interferometric (with optical heterodyne detection system) space-integrating spectra analyzer with two Bragg cells is presented after I.C. Chang [81]. The cells are supplied with the RF input signal (being analyzed) and a broad-band reference signal, respectively. The diffracted light from the input signal cell and from the reference cell are combined, specially Fourier transformed and added at the detector plane where the spectrum is recorded against frequency selected in the heterodyne process by filtering components of reference signal.

The Fig. 27 represents a two beam SAW time-integrating correlator [79]. The input signals S_1 and S_2 drive two tilted transducers, so that the two SAW have titled wave-fronts, however thanks to the anisotropy of the material (lithium niobate) they both travel along z - axis. Two light beams (splited from the incidenting beam) are strongly interacting at Bragg angles and combined together. In detecting signal at the output the correlation function of the input signals S_1 and S_2 may be recognized and selected.

OTHER APPLICATIONS IN SELECTED DOMAINS OF RESEARCH AND PRACTICE

Acoustooptics provides measurement methods of minimal errors. The main feature of them consists in the fact that measurements do not disturb the system being a subject of examination. An acoustical information required is being transformed into optical one in the acoustooptical interaction process. That allows to perform local measurements "in situ" in the acoustical field far from an acoustical transducer. Acoustooptical methods provide:

a) acurate measurements of sound velocity in iso- and anisotropic media giving possibilities of determination elastic constants (in linear and in nonlinear range),

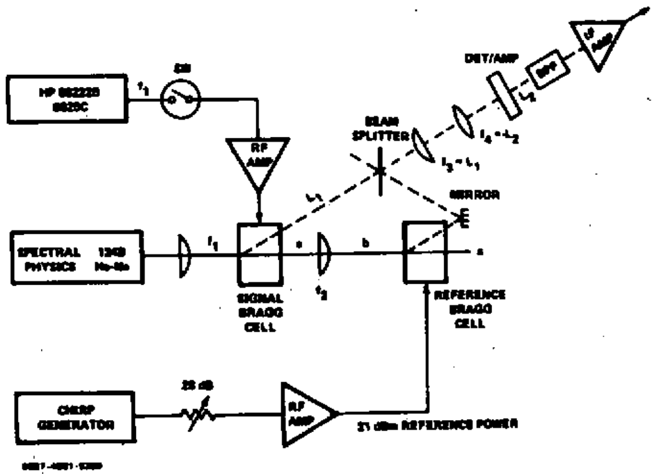


Fig. 26 after [81]

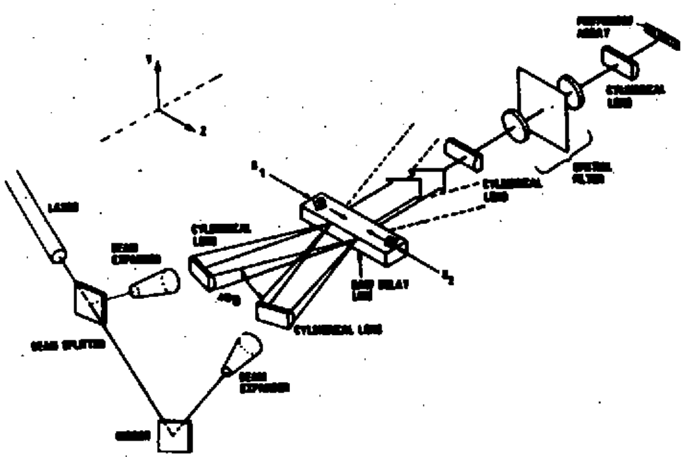


Fig. 27 after [79]

b) accurate measurements of attenuation giving a way for determination of viscosity coefficients, thermodynamic and molecular characteristics, relaxation times etc.,
c) measuring light polarization states allowing to determine elements of molecular structure.
Obtaining the informations listed above for every medium is important. For anisotropic media including anisotropic liquids the item c) gives many possibilities. Biological tissues and biological liquids have anisotropic structure and many of them are liquid crystals.
Many interesting acoustooptical measuring methods have been elaborated which gave possibilities of applying in liquid crystals, organic and bio-liquids examinations:
a) methods based on variation of transmission of light induced by acoustical deformation in anisotropic liquids.
There are two methods of examination of ordered liquid systems in the polarized light beam [103-111]:
The orthoscopic method (the light beam is parallel) Fig. 28 and the conoscopic method (the light beam is convergent) Fig. 29. The cells in which the liquid to be examined is situated are specially designed to enable measurements for various orientations of molecules (homeotropic or planar) respect to the direction of the wave propagation and the direction of deformation. Usually, the thickness of the cells is small comparing with the wavelength.
b) Methods based on diffraction of light by ultrasound. In those methods the cells are rather long comparing to the wave length and both kinds of ultrasonic-light diffraction may be applied: the Raman-Nath (Fig. 4a) and Bragg (Fig. 4b). The diffracted light beams are detected and the intensity of light and its frequency modulation in separate orders are measured against ultrasonic power and frequency. In the case of anisotropic media the diffraction of light by ultrasonics is associated with characteristic variations in the state of polarization [103,110-114]

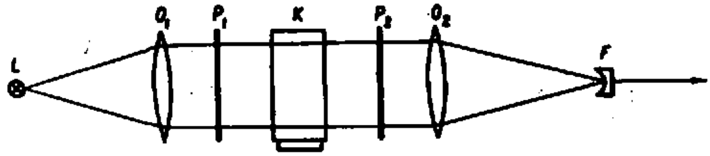


Fig. 28

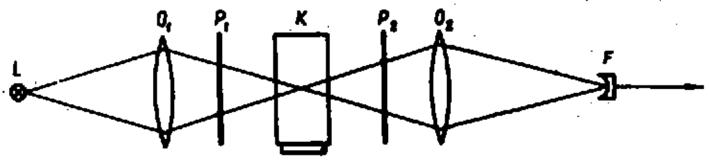


Fig. 29

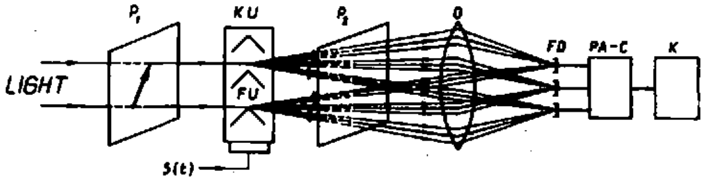


Fig. 30

what can be used for getting information about molecular structure of the medium [104]. The Figs 30 and 31 present the schemes of two arrangements which are being used in our laboratory for anisotropic liquid examinations. [The other acoustooptical method based on Bragg diffraction phenomena and applied in traditional reverberation method has been developed by the Japanese group in Tokio (Takagi et al [107-109]) which is called HRB (High Resolution Bragg) method. The scheme of the arrangement is presented in the Fig. 32 [107]. The beam reflected at the Bragg angle is recorded using the heterodyne technique for optical signals (incidenting and scattered ones) against the angle of incidence. The recorded curve represents a Fourier spectrum of wave vectors of the waves reverberating in the cell after a pulse excitation with the ZnO transducer. The Bragg angle determines the ultrasonics velocity and the half band-width of the curve recorded - the attenuation coefficient. An example of the curves for the carbon di-sulfide is presented in the Fig. 33. The method enables measurement with great accuracy of attenuation (0.5 - 1%) and velocities (0.05%) in the large range of frequency to discover relaxation and dispersion regions in liquids. In many bioliquids the relaxation processes could not be explained on the base of the single (or discret number) relaxation time theory [105-106] but a spectrum of relaxation times must be considered. The Fig. 34 represents frequency dependence of the ultrasonic absorption coefficient α/f^2 in the egg albumine obtained by Choi et al [105], which is an evident example of the un-usual behaviour suggesting very complicated molecular processes involved in the ultrasonic absorption. Dependence on frequency is aproximated by the formula $\alpha = c \cdot f^{1.27}$, where c - const, f - frequency. It would be necessary to talk about many other applications of acoustooptics for instance in solid state physics examinations [126,127] and composite materials studies [119].

The acoustooptical interactions taking place in optical waveguides (fibers) [136-140] being influenced by extermal strains

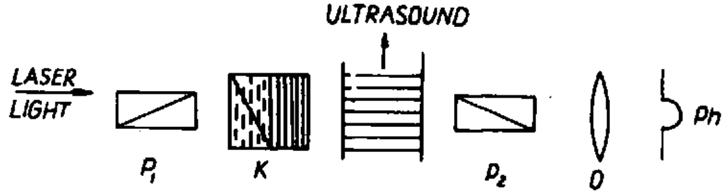


Fig. 31

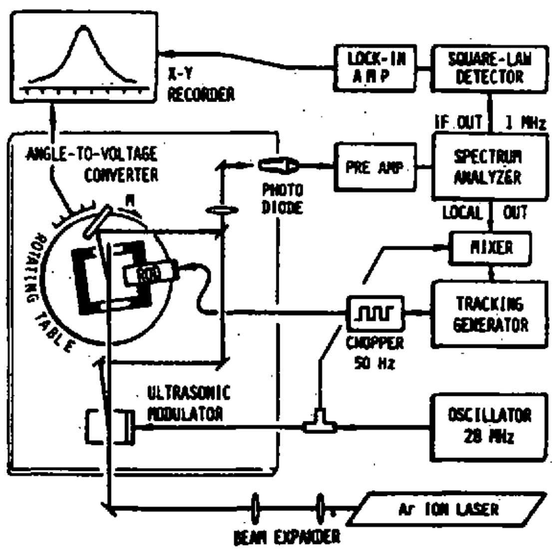


Fig. 32 after [107]

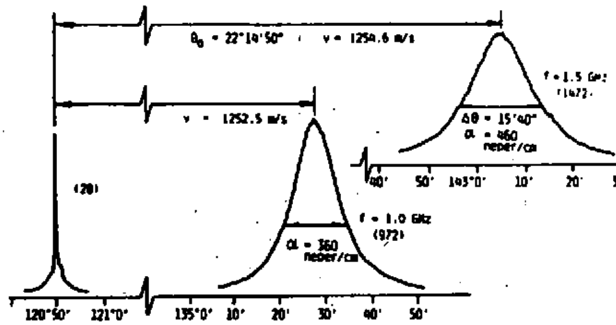


Fig. 33 after [107]

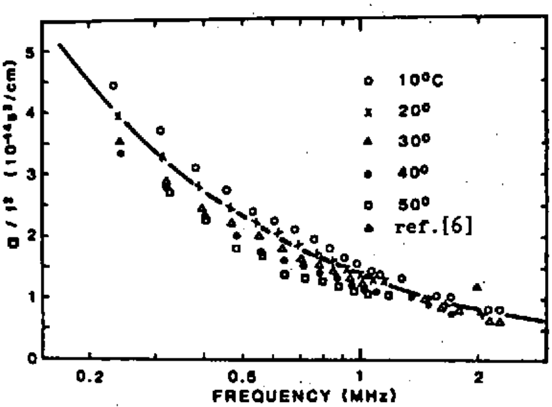


Fig. 34 after [105]

and deformations could be an interesting topic of a seperate lecture, too, as many others. The long list of references quoted in the historical survey given at the begining of this review can provide much more information on the interesting and actual subject.

CONCLUDING REMARKS

In the review acoustooptical interaction phenomena were presented in their historical and actual, physical and practical aspects.

The domain is very wide and recently, intensively cultivated so in research as well as in applications. The most perspective for development seems to be acoustooptic interferometry, especially in the fast holographic photography, application of light diffraction by ultrasound in material examination anisotropic solids and liquids including bio-liquids as well as in constructing a.o. devices for signal processing. The SAW processors are very promising in integrated optics. Recently, a great interest has been worked up in acoustooptical interactions using optical waveguides for constructing extremaly sensitive optical fiber sensors.

REFERENCES

1 1-st Spring School on Acoustooptics and Applications, Gdańsk University, 1980 (a report in Ultrasonics 19, 44, (1981)).
2 2-nd Spring School on Acoustooptics and Applications, Gdańsk University, 1983 (a report in Ultrasonics 22, 45, (1984)).
3 3-rd Spring School on Acoustooptics and Applications, Gdańsk University, 1986 (a report in Ultrasonics 25, (1987)).
4 P. Biquard, C.R. Lucas, Acad. Sci. Paris, 195, 121, (1932).
5 P. Debye, F.W. Sears, Proc. Nat. Acad. Sci. U.S. 18, 410, (1932).
6 R. Mertens, Fifty years of acousto-optics, Proc. 11-th ICA, Paris, 8, 101, (1983).
7 L. Brillouin, Ann. Phys. Paris, 17, 88, 1922 ; Actual Scient. Ind., 59, (1933).
8 L.I. Mandelsztam, Zh. Russ. Fiz. Khim. 58, 381, (1926).
9 G. Landsberg, L. Mandelsztam, Naturwiss. 16, 557, 772, (1928).
10 C.V. Raman, K.S. Krishnan, Proc. Roy. Soc., A117, 1, (1927); Phil. Mag., 5, 498, (1928).

11 E. Gross, Nature, 126, 201, 400, 603, (1930).
12 F. Pockels, Ann. Physik 39, 440, (1890).
13 A. Toepler, Oswald Klassiker der Exact. Wissensch., 157, (1906); 158, (1906).
14 P. Greguss, Proc. of Ultr. Intern. 83, Halifax, 104-109, (1983).
15 C.V. Raman, N.N. Nath, Proc. Ind. Ac. Sci. A2, 406, (1935); A2, 414, (1935); A3, 119, (1936); A3, 459, (1936).
16 O. Nomoto, J. Phys. Math. Soc. Jap., 22, 314, (1940).
17 R. Extermann, G. Wannier, Helv. Phys. Acta, 9, 337, (1936).
18 R. Lucas, P. Biquard, J. Phys. Radium, 3, 464, (1932).
19 S.M. Rytov, Proc. Acad. Sci. S.U., 223, 1937 .
20 E.H. Wagner, Z. Phys., 141, 604, (1955).
21 F. Kuliasko, R. Mertens, O. Leroy, Proc. Ind. Acad. Sci., 68, 295, (1968).
22 O. Leroy, Proc. Ind. Acad. Sci. 68, 296, (1968); 63, 19, (1971); 73, 109, 232, (1971); Ultrasonics, 10, 183, (1972).
23 R. Mertens, Simon Stevin J., 27, 212, (1949/50); Proc. Ind. Acad. Sci., 42A, 195, (1955).
24 P. Phariseau, Proc. Ind. Acad. Sci., 44, 44, (1956).
25 E.A. Hiedemann, E.Z. Schreuer, Z. Physik, 107, 463, (1937).
26 I.G. Michaylov, V.A. Schutilov, Akust. Zhurn., 4, 174, (1958).
27 W.G. Mayer, G.B. Lamers, G.G. Auth, J. Acoust. Soc. Am., 42, 1255, (1967); Proc. Ultr. Intern. 85, London, 170-174, (1985).
28 L.E. Hargrove, J. Acoust. Soc. Am., 34, 10, 1547, (1962).
29 W.R. Klein, B.D. Cook, IEEE Trans. SU-14, 123, (1967).
30 M.A. Breazeale, E.A. Hiedemann, J. Acoust. Soc. Am. 30, 8, 751, (1958); 31, 24, (1959).
31 S. Bhagavantam, B.R. Rao, Nature 161, 927, (1948).
32 W.R. Klein, E.A. Hiedemann, Physica, 29, 981, (1963).
33 P.M. Mejias, Appl. Optics, 19, 263, (1980).
34 M.G. Mohran, T.K. Gaylord, R. Magnusson, Opt. Comn., 32, 14, (1980).
35 R. Magnusson, T.K. Gaylord, J. Opt. Soc. Am., 68, 809, (1978).
36 P. Kwiek, O. Leroy, A. Markiewicz, A. Sliwiński, Proc. of Ultr. Intern. 83, Halifax, 110, (1983).
37 V.N. Parigin, I.E. Chirkov, Sov. J. Quant. Electron., 5, 180, (1975).
38 A. Korpel, IEEE Trans. SU-15, 115, (1968).
39 L. Bergmann, E. Fues, Z. Physik 09, 1, (1938).
40 M.A. Govinda Rao, Proc. Ind. Acad. Sci., 8A, 6, (1938).
41 N.S. Nagendra Nath, Proc. Cambr. Phil. Soc., 34, 213, (1938).
42 B. Ramachandra Rao, Proc. Ind. Acad. Sci., 29A, 16, (1949).
43 K. Nagashushana Rao, Proc. Ind. Acad. Sci., 8A, 124, (1938).
44 J.S. Murthy, J. Acoust. Soc. Am., 26, 970, (1954).
45 K.L. Zankel, E.A. Hiedemann, Naturwissensch. 45, 157, (1958).
46 R. Mertens, Proc. Ind. Acad. Sci. 48A, 288, (1958); 50A, 289, (1959); 55A, 63, (1962).
47 M. Pancholy, S. Parthasarathy, J. Sci. Industr. Res. 58, 1, (1946).

48 R.R. Aggarwal, M. Pancholy, S. Parthasarathy, J. Sci. Industr. Res., 98, 107, (1950).
49 R.R. Aggarwal, Acustica, 2, 20, (1952).
50 P. Phariseau, Physica, 25, 917, (1959); 30, 1813, (1964).
51 R. Mertens, Proc. Ultras. Intern., 214, (1975).
52 R. Mertens, Simon Stevin, 53, 111, (1979).
53 F. Kuliasko, R. Mertens, Simon Stevin, 34, 126, (1961).
54 R. Mertens, Simon Stevin, 28, 164, (1951).
55 G. Plancke-Schuyten, R. Mertens, O. Leroy, Seminarie Analytische Mechanica, B-9000 Gent I, (1971); II, (1972).
56 R. Mertens, Z. Physik, 160, 291, (1960).
57 L.E. Hargrove, E.A. Hiedemann, R. Mertens, Z. Physik, 167, 326, (1962).
58 O. Leroy, J. Sound Vibr. 26, 289, (1973); 32, 241, (1974); Acustica, 29, 303, (1973).
59 P. Kwiek, O. Leroy, A. Sliwiński, FASE 78, II-37, 193, (1978).
60 P. Kwiek, A. Sliwiński, O. Leroy, Proc. Ultrasonics Intern. 79, Graz, 494, (1979).
61 O. Leroy, E. Blomme, CETHEDEC Symposium, Paris, (1980); Ultrasonics, 19, 173, (1981).
62 O. Leroy, P. Kwiek, A. Sliwiński, Proc. 1-st Int. Symp. on Ultrasonic Materials Characterisation, N.B.S., Gaithersburg, 657-663, (1978).
63 O. Leroy, E. Blomme, P. Kwiek, A. Markiewicz, A. Sliwiński, Proc. of Utr. Intern. 81, Brighton, 98, (1981).
64 O. Leroy, A. Sliwiński, P. Kwiek, A. Markiewicz, Ultrasonics, 20, 135, (1982).
65 P. Kwiek, Pole bliskie i dalekie w zjawisku ugięcia światła na dwóch falach ultradźwiękowych, Wyd. Uniwersytet Gdański, Rozprawy i monografie, 1-78, (1985), in Polish.
66 E. Blomme, P. Kwiek, O. Leroy, A. Markiewicz, A. Sliwiński, Proc. of Ultr. Inter. 85, London, 533-538, (1985).
67 O. Leroy, E. Blomme, Proc. of 2-nd Spring School on Acousto-optics, Gdańsk, 125-157, (1983).
68 F. Calligaris, P. Ciuti, I. Gabrielli, Acustica, 38, 37-43, (1977).
69 I. Gabrielli, P. Ciuti, Proc. of 1-st Spring School on Acoustooptics, Gdańsk, 120-135, (1980).
70 I. Gabrielli, P. Ciuti, Proc. of 2-nd Spring School on Acoustooptics, Gdańsk, 84-96, (1983).
71 K. Patorski, Proc. 2-nd School on Acoustooptics and Applications, Gdańsk, 32-58, (1983), Ultrasonics 19, 169, (1981).
72 M.V. Berry, The diffraction of light by ultrasound, Academic Press, London, 1966.
73 M. Born and E. Wolf, Principles of Optics chap. 12, 3-rd ed. N.York, 1965.
74 T. Tamir, Topics in Applied Physics, Integrated Optics, 7 Springer Verlag, New York, 1975.
75 J. Sapriel, L'Acousto-optique, Collection de Monographe de Physique, 11, Masson, Paris, 1976.

76 W.P. Mason, R.N. Thurston, Physical Acoustics, Acad. Press, New York, 7, 61, 1970 .
77 R.G. Hunsperger, Integrated optics: Theory and Technology, Springer Vlg, 1984 .
78 W.I. Balakshii, W.N. Parigin, L.E. Chirkov, Fizicheskiye Osnovi Akustooptiki, Radyo i Zvyaz, Moskva, 1985 .
79 N.J. Berg, Proc. Ultr. Intern. 85, London, 183-188, (1985).
80 C. Garvin, N.J. Berg, R. Felock, ibid, 429-434.
81 I.C. Chang, ibid, 175-182.
82 R. Reibold - private communication.
83 G.P.P. Gunarathne, J. Szilard, Proc. Ultr. Inter. 83, Halifax, 74-78, (1983).
84 A.E. Ennos, Hologram interferometry, Adv. in Quantum Electr. N. York - London, 1970 .
85 R.J. Collier, Optical Holography, Ac. Press, N. York - London, 1972 .
86 R. Reibold, Acustica 38, 263, (1977).
87 P. Kwiek, A. Śliwiński, Arch. Acoust., 4, 65-72, (1979).
88 P. Kwiek, A. Śliwiński, I. Wojciechowska, Proc. Colloq. Ultrasonore Franco-Polonais - Paris, 189-230, (1978).
89 P. Kwiek, A. Śliwiński, I. Wojciechowska, Ultrasonics, 17, 159-165, (1979).
90 I. Wojciechowska, A. Śliwiński, Ultrasonics, 19, 115-119, (1981).
91 P. Kwiek, A. Markiewicz, A. Śliwiński, Acoust. Letts 3, 215-218, (1980).
92 P. Kwiek, I. Wojciechowska, A. Śliwiński, Proc. Colloq. Ultrasonore, Franco-Polonais, Jabłonna, 125-134, (1980).
93 P. Kwiek, Acoust. Letts 5, 115-119, (1982).
94 R. Reibold, Proc. 1-st Spring School on Acoustooptics and Appl., Gdańsk, 186-197, (1980).
95 A. Śliwiński, ibid, 136-185.
96 R. Reibold, Proc. 2-nd Spring School on Acoustooptics and Appl., Gdańsk, 272-287, 1983 ; Proc. 3-rd Spring School on Acoustooptics and Appl., Gdańsk, 113-124, (1986).
97 I. Wojciechowska, A. Markiewicz, Proc. 2-nd Spring School on Acoustooptics and Appl., Gdańsk, 288-297, (1983).
98 L. Bergmann, Der Ultraschall und Seine Andwendung in Wissenschaft und Technik, Zurich, 1949 .
99 A. Sliwiński, Akustooptyka a procesy molekularne, Postępy Fizyki Molekularnej, IFM PAN, Poznań, 2, 113-129, (1985), in Polish .
100 M. Kosmol, A. Sliwiński, Acta Phys. Pol. A50, 375-382, (1976).
101 M. Bader, P. Martinoty, Proc. Ultr. Intern. 81, Brighton, 94-97, (1981).
102 M. Kosmol, A. Sliwiński, Arch. Acoust. 4, 117-130, (1979).
103 M. Witkowska-Borysewicz, A. Sliwiński, J. de Phys. 44, 411-420, (1983).
104 A. Śliwiński, Proc. UBIOMED VII, Eisenach, 1986 , in printing .

105 P.K. Choi, J.R. Bac, K. Takagi, Proc. 12 ICA, Toronto, 2, G1-1, (1986).
106 K.G. Breitswerdt, S. Gut, ibid, 2, G2-6.
107 K. Takagi, P.K. Choi, H. Ozawa, ibid, 2, G2-1.
108 K. Takagi, K. Negishi, J. Phys. D15, 757, (1982).
109 K. Takagi, Proc. 11 ICA, Paris, 2, 33, (1983).
110 O.A. Kapustina, Akustoopticheskiye svoystva zhidkikh kristalov, A.N. USSR, 1979 .
111 A.P. Kapuśtin, O.A. Kapustina, Akustika zhidkikh kristalov, Izd. Nauka, Moskwa, 1986 .
112 A. Alippi, 1-st Spring School on Acoustooptics and Appl., Gdańsk, 250-259, (1980).
113 A. Alippi, Proc. of Ultr. Intern. 85, London, 189-194, (1985).
114 A. Alippi, A. Palma, L. Palmieri, G. Socino, E. Verona, Proc. of Ultr. Intern. 77, Brighton, 125-130, (1977).
115 M. Szustakowski, P. Loranc, Proc. 1-st Spring School on Acoustooptics and Appl., Gdańsk, 260-270, (1980).
116 A. Drzewicka, M. Szustakowski, ibid, 271-284.
117 D.F. Nielson, Electric, Optic and Acoustic Interaction in Dielectrics, J. Willey and Sons, N. York, 1979 .
118 A. Alippi, Proc. of 2-nd Spring School on Acoustooptics and Appl., Gdańsk, 263-271, (1983).
119 J. Sapriel, Proc. of 3-rd Spring School on Acoustooptics and Appl., Gdańsk, 70-82, (1986).
120 A. Śliwiński, Proc. 2-nd Spring School on Acoustooptics and Appl., Gdańsk, 244-262, (1983).
121 A. Sliwiński, Proc. 3-rd Spring School on Acoustooptics and Appl., Gdańsk, 83-105, (1986).
122 M.A. Breazeale, Proc. of 1-st Spring School on Acoustooptics and Appl., Gdańsk, 69-81, (1980).
123 W. Hereman, F. Verheest and R. Mertens, Acustica, 48, 1-9, (1981).
124 W. Hereman, Proc. of 2-nd Spring School on Acoustooptics and Appl., Gdańsk, 206-223, (1983).
125 A. Defebvre, Proc. of 2-nd Spring School on Acoustooptics and Appl., Gdańsk, 182-205, (1983).
126 A. Zarembovitch, F. Michard, B. Perrin, Proc. of 1-st Spring School on Acoustooptics and Appl., Gdańsk, 82-85, (1980).
127 F. Michard, Proc. of 2-nd Spring School on Acoustooptics and Appl., Gdańsk, 422-427, (1983).
128 L.E. Hargrove, J. Acoust. Soc. Am. 43, 847-851, (1968).
129 T.H. Neighbors, W.G. Mayer, J. Acoust. Soc. Am. 74, 146-152 (1983).
130 R.N. Zitter, J. Acoust. Soc. Am. 43, 864-870, (1968).
131 E. Hansler, W.G. Mayer, M. Schwartz, Acoust. Letts, 4, 180-184, (1981).
132 W.G. Mayer, T.H. Neighbors, Proc. 3-rd Spring School on Acoustooptics and Appl., Gdańsk, 8-21, (1986).
133 A. Markiewicz, ibid, 34-45.
134 P. Kwiek, R. Reibold, Acoust. Letts, 7, 167-172, (1984).

135 R.O.Claus, J.H.Cantrell Jr,Acoust.Letts,5, 1-4 ,(1981).
136 G.M. Sessler, Proc. of 11-th ICA, Paris, 13-26,(1983).
137 B. Culshaw, J. Phys. E. Sci. Instr. 16, 978,(1983).
138 A. Opilski, Proc. of 2-nd Spring School on Acoustooptics and Appl., Gdańsk, 328-354,(1983).
139 M. Szustakowski, ibid, 460-479.
140 B.A. Krasyuk, G.I. Kornyeyev, Opticheskiye sistemy svyasi i svetovodniye datchiki, Izd. Radyo i svyas, Moskva, 1985 .
141 S. Nagai, Ultrasonics, 23, 77-82,(1985).
142 P. Kwiek, A. Markiewicz, A. Śliwiński, Acoust. Letts, 3, 16-22,(1979).
143 W. Lauterborn, W. Hentschel, Ultrasonics, 23, 260-268, (1985).
144 N.J. Berg, J.N. Lee, Editors, Acousto-Optic Signal Processing, Marcel Decker, Inc. N. York, 1982 .