ACOUSTO-OPTICS - 70-TY YEARS AFTER FIRST ULTRASONIC LIGHT DIFFRACTION EXPERIMENTS

PACS no.43.35.Cg, 43.35.Sx

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ABSTRACT

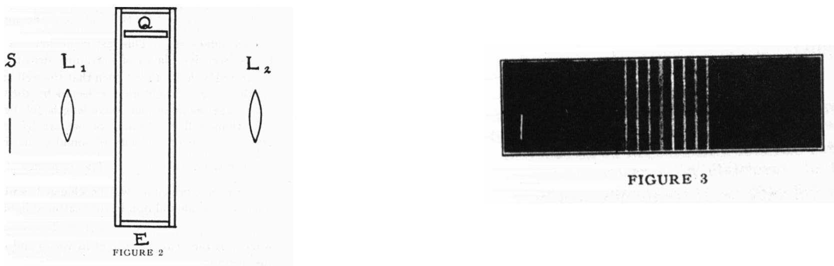
In 1932 two independent experiments performed by R. Lucas and P. Biquard in France and by Debye and Sears in USA which originated investigations on the ultrasonics and light interaction initiating the new branch of science and applications widely developed nowadays as acousto-optics. Original figures from their papers [2,3] are reminded and followed by historical survey. Some mile stones of the acousto-optics achievements and fundamental concepts for ultrasonic light diffraction description are shortly reviewed. A large number of references of recent publications reflects the state of art. Of the subject both in the theoretical and application aspects and shows perspectives of further development of the fascinating branch of physics and optical engineering.

INTRODUCTION

C.V. Raman and N.S. Nagendra Nath at the begining of the first of several papers [1] in 1935 wrote: „As is well known, Langevin showed that high frequency sound waves of great intensity can be generated in fluids by the use of piezo-electric oscilators of quarz. Recently Debye and Sears in America and Lucas and Biquard in France have described very beautiful experiments illustrating the diffraction of light by such high-frequency sound waves in a liquid". The statement „very beautiful experiments" speaks itself in the light of the 70 years history of acousto-optics the origin of which may be dated from 1932 when the two independent papers of those authors [2,3] appeared. The date is significant as the starting point for systematic examinations of the interaction of light and ultrasonics. Fundamental theoretical and experimental papers were subsequently published in the 1930s [1-8]. However, looking further back into the history one finds Brillouin's [9] theoretical papers on interaction of light and elastic waves (present in elastic medium as thermal density fluctuations) which stimulated experiments by Mandelsztam [10], Lansberg and Mandelsztam [11], Raman and Krishnan [12] and Gross [13] on light scattering in liquids. The Brillouin's prediction of light and sound interaction has been a background for Debye and Sears [2] as well as for Lucas and Biquard [3] investigations who verified the theory, hence, some times the date 1922 is considered [14, 15] as the begining of acousto-optics, however, as recognized by Mertens [13] and others [17, 18] the 1932 is the origin of the new field of science which since that time has started to develope consequently.

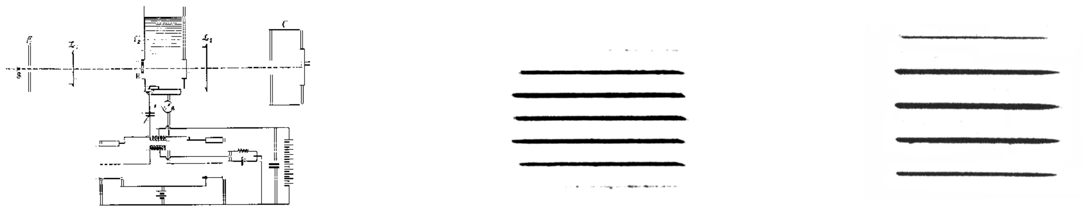
SOME MILE STONES IN ACOUSTO-OPTICS HISTORY

The „beautiful experiments" (Fig 1 and 2) which were stimulated by Brillouin's prediction occured suprisingly rich in respect to the large number of diffraction orders simmetrically spaced about the undifracted beam (Fig 1b, 2b,c). Brillouin [9] has predicted only ±1 orders of diffraction for a sinusoidal sound wave. As it has occured later it was in fact a good prediction of the acousto-optic Bragg



a) b)

Fig 1. Original Debye and Sears' optical arrangement for the ultrasonic light diffraction (a) and the original spectrum of multiple diffraction orders (b) for 5.7 MHz after [2].



a) b) c)

Fig 2. Original Lucas and Biquard experimental arrangement for the ultrasonic light diffraction (a) and their original spectra of multiple diffraction orders for 30.3 in the water (b) and 30.3 MHz in petroleum ether (c).

diffraction only confirmed experimentally by Bhagavantam and Rao [19] in 1948. Debye and Sears as well as Lucas and Biquard have not observed any selected Bragg angle but discovered multiple orders diffraction spectrum dependent on supersonics frequency and electric power applied to the transducer and their results obtained were conceded as Brillouin's prediction was wrong. The observations had not been predicted and many efforts were made to explain the appearance of multiple diffracted orders.

Debye and Sears [2] discussing their results have stated that in their experimental conditions the Bragg reflection angle was not „sharply defined ... Only if L/Λ is large compared to Λ/λ does a sharp definition of Bragg's angle exist". (L is the lenght of the path of light in the liquid and Λ, λ - wavelengths of supersonic and light wave, respectively). It is easy to recognize, that the above statement formulates a criterion for what is now called the Bragg regime and there is straight relation between the Q parameter defined in 1967 by Klein and Cook [20] and the Debye - Sears ratio $L\lambda/\Lambda^2$ as shown by Korpel [14]:

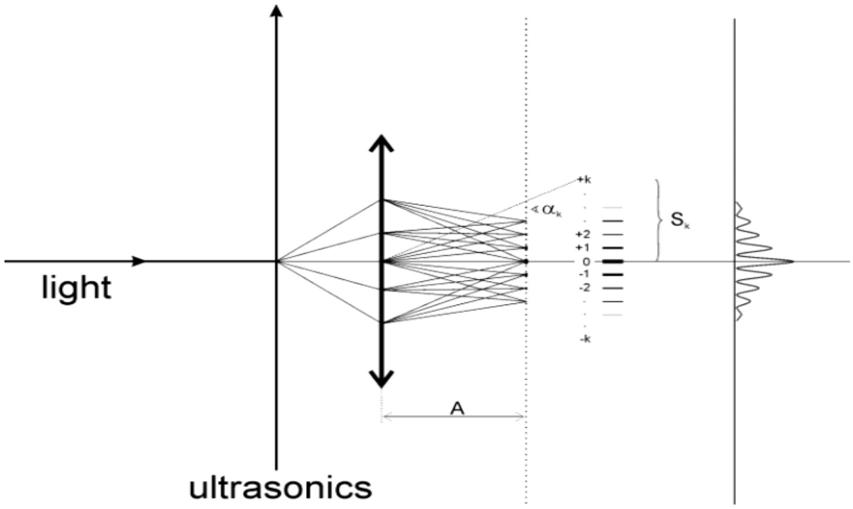
$$Q = K^2L/k = 2\pi L\lambda/\Lambda^2 = 2\pi \text{ x Debye - Sears ratio} \tag{1}$$

where $K = \dfrac{2\pi}{\Lambda}$ and $k = \dfrac{2\pi}{\lambda}$.

The theory of Lucas and Biquard [3] based on calculation of ray trajectories producing an amplitude diffraction grating at the output plane has described the phenomenon in proper but not completed way, however they did not calculate the light intensity distribution in the spectrum. Next, their theory was developed by Nomoto [4] and compared successfully with experiments, however the complete ray trajectories theory valid for a thick ultrasonic column was elaborated much later by Berry [21]. More recent contributions to that approach for a thick column case were done by Defebvre [22] and Kwiek [23].

Debye and Sears as well as Lucas and Biquard could not satisfactorily explain their results, particularly the presence of multiple orders in diffraction pattern. In 1933 Brillouin [24] put forward the hypothesis that multiple orders were the results of concecutive rescattering of light passing a finite path of the ultrasonic column. The Brillouin's explaining has waited until 1966 for quantitative evaluation given by Berry's [21] concept of mathematical operator formalism applied to the interaction of a light beam with the ultrasonic column and generalised in 1980 by Korpel and Poon [25] who formulated the theory of multiple scattering of plane light waves composing an arbitrary light field by the plane waves of ultrasound composing an arbitrary sound field. In both theories the Feyman diagrams have been used for illustration of the formalism and visualisation of the physical picture of the phenomenon.

The most important theory in 1930's explaining the ultrasonic light diffraction phenomenon was delivered in a series of papers (already mentioned above) by Raman and Nagendra Nath [1]. Their first approximated theory has assumed a thin column of ultrasonics as a phase grating in which a curvature of



a) b) c)

Fig 3. Raman-Nath model of the ultrasonic light diffraction for normal incidence: a)interaction and diffraction scheme, b) diffraction pattern at the focus plane of a lense, c) light intensity distribution in diffraction pattern for several orders.

light rays could be neglected (as in the geometry in Fig 3). As the next steps they considered oblique incidence case, Doppler shift of light frequency in diffracted orders and finally derived exact recurrence relation between diffraction orders which is known as classical Raman-Nath system of equations. In nowadays form the equations are following

$$2l\frac{d\psi_n}{\partial z} - \upsilon(\psi_{n-1} - \psi_{n+1}) = inQ(n-\beta)\psi_n, \qquad \psi_n(0) = \delta_{n,o} \qquad (n \in Z) \tag{2}$$

where ψ_n are the diffracted light amplitudes of a given order n; z refers to the direction perpendicular to the ultrasonic wave; $\upsilon = 2\pi L\mu_1/\lambda$ is the Raman-Nath parameter and $Q = = 2\pi\lambda L/\mu_o\Lambda^2$ the Klein-Cook parameter (mentioned above in (1) where μ_o is not present), μ_o represents the refractive index of the medium and μ_1 its maximum variation due to the ultrasonics disturbence; λ and Λ are the wavelength of light and ultrasound, respectively. Finaly, β is the angle of incidence of light expressed in units of the Bragg angle $\theta_B = \text{Arcsin}(\lambda/2\Lambda\mu_o)$.

The Raman-Nath equation system can be solved exactly in two cases: for $Q \rightarrow 0$ (what corresponds to the Raman-Nath regime of ultrasonic light diffraction determined as $Q \ll 1$) and for $Q \rightarrow \infty$ (what corresponds to the Bragg regime determined as $Q >> 1$). In the intermediate (or transit) regime i.e. between Raman-Nath and Bragg ones only approximative methods of solution are applied (for example the N-th order approximation method (NOA method) for normal incidence [26] or M-th, N-th order approximation metod (M,N-OA) for oblique incidence [27].

Returning again to 1930's one should mention about theoretical papers of Wannier and Exterman [5] and Rytov [6] and about many other experiments performed by S. Parthasarathy in India, O. Nomoto in Japan, E. Hiedemann in Germany, F.H. Sanders in Canada, R. Bär, L. Ali, F. Levi in Switzerland, C. Schaefer and L. Bergman in Germany whose book (first edition) appeared in 1937 and the 5-th edition in 1954 [8].

Further fundamental contributions appeared in 1950-ties. Bhatia and Noble [28] showed a new approach leading to an integral equation system for diffraction field solution. An exact treatment of the Raman-Nath system was given by R. Mertens and his group [29-32] and O. Leroy and his group [33-36]; Basic experiments before the laser discovery were performed in USA by Hiedemann and his group [20, 37-41] and Michailov and Shutilov in Russia [42], however, only limited applications were made with incoherent light in pre-laser era (before 1962), when the invention of the laser changed the situation dramatically and a great progress in acousto-optics have started in the post-laser era.

Examination of Klein and Cook (1967) [20] for isotropic and of Dixon (1967) [43] for anisotropic media of light and ultrasonic interactions are mile stones for next explosive growth of development in acousto-optics and its applications. Many groups in the world have been involved in the research and several fundamental books, reviews and conference proceedings have appeared on the subject [15, 18, 21, 44-59]. Many acousto-optical devices for signal processing as light modulators, deflectors, filters, convolvers, correlators and analyzers were developed and applied in many fields of science and technology as well as in practical optoelectronics, photonics etc. [44,46,49,50,52,56,59]. The interest in practical applications of acousto-optics has involved demand of special acousto-optic materials investigated in order to get optimal parameters such as diffraction efficiency, depth of modulation, bandwidth, etc. Many of materials investigated were anisotropic (like many natural crystals or glasses under internal or external stresses) and the efect of birefringence has appeared of special advantage in acousto-optic devices [15,43,45,46,50,51,52,57].

The fundamental coupled plane - wave concept leading to the wave vectors diagrams, already indicated by Debye and Sears [2] (Fig 4) which has expressed the condition for phase synchronous interaction necessary for the acousto-optic diffraction formulated by Brillouin [9] and much later developed by Kroll [63] has been developed as very useful approach so in theoretical as well as in practical designing of acousto-optical devices.

The wave vector diagrams corresponding to the relations

$$\vec{k}_i + \vec{K} = \vec{k}_+ \quad \text{for upshifted} \quad \text{and} \quad \vec{k}_i - \vec{K} = \vec{k}_- \quad \text{for downshifted interaction} \qquad (4)$$

are presented in Fig 5. $\vec{k}_i$ represents the incident light plane wave, $\vec{K}$ ultrasound plane wave and $\vec{k}_+, \vec{k}_-$ light plane waves diffracted up and down, respectively.

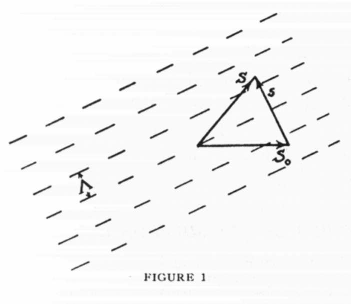


Fig 4. Original Debye and Sears' vector diffraction diagram (after [2])

In the quantum mechanical context the relations (4) correspond to the conservation of momentum in the interaction process of photon and phonon. The quantum energy conservation of the process may be expressed as

$$hf \pm hF = hf_\pm \qquad (5)$$

where f and $f_\pm$ denote light frequences and F the sound frequency, h is Planck constant. The relations (5) describe the Doppler shift of the light frequency in the up and down diffracted light beams, respectively.

In parallel to applications of Raman-Nath system of equations (2) the phase mismatch method was elaborated [44,50,64] and the respective system of differential equations was derived for calculations of diffraction orders amplitudes $\varphi_n(x)$:

$$\frac{d\varphi_n}{dx} = \frac{\upsilon}{2L}\varphi_{n-1}\exp jk_{n-1}x - \frac{\upsilon}{2L}\varphi_{n+1}\exp(-j\Delta k_n x) \qquad (6)$$

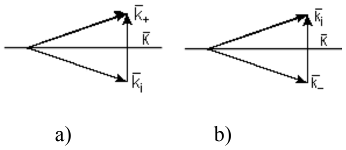


Fig 5. Vector diagrams for upshifted (a) and downshifted (b) interaction

where the mismatch vectors $\Delta\vec{k}_n$ are determined by the relation

$$\vec{k}_{n-1} + \vec{K} + \Delta\vec{k}_{n-1} = \vec{k}_n$$

The vector diagrams have occured very useful for both models as for Raman-Nath approach as well as for the phase maching one, however, there are different geometrical pictures for both cases [15,50,64,65]. Fig 6 shows an arbitrary selected example of the mismatch model for Bragg acousto-optical interaction in anisotropic case [65].

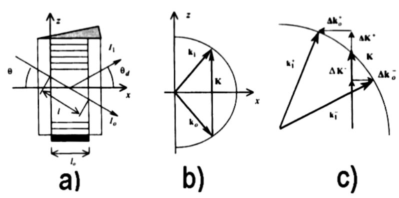


Fig 6. Bragg acousto-optic interaction in acoustically isotropic medium: scheme of diffraction (a) wave vector diagram of interaction (b) vector diagram illustrating violation of synchronism condition (c) (after Voloshinov and Makarov [65])

Many investigations were carried out to study the nature of the ultrasonic light diffraction in some special configurations in particular in the case of two parallel ultrasonic beams. The theoretical results elaborated by Leroy [66,67] were the subject of experimental verification [68] what stimulated further examination in co-operation with other than Belgian groups and many interesting results were published [69,70,71,72]. Modulation of ligh effects by two separate or adjacent parallel or antiparallel ultrasonic beams were reviewed in [73] where several possibilities of geometry of the mutual interaction between light and ultrasonic beams were considered. It was shown for systems of two ultrasonic beams where the frequency ratio were harmonic, $f_1 : f_2 = 1 : n$ or $m : n$ (n, m being integers) that the light intensity distribution in diffraction orders depends on the phase shift δ between the beams. The regular modulation of light intensity in diffraction orders against δ has been theoreticaly predicted [66,67] and experimentally proved [68,69].

All modulation effects in the light intensity distribution after interacting with two ultrasonic beams are the consequences of the amplitude and phase relations in the diffracted light beams which are determined along the path of interaction in each of the ultrasonic beams separately and depending on their mutual configuration as well. These relations were studied by Gabrielli with the phase vector analysis [74]. Blomme [48] theoretically and Kwiek and Markiewicz [75,76] and Kwiek and Reibold [70,71] have shown that the ultrasonic light diffraction system treated as an amplitude - phase grating had a strong influence on light diffraction distribution. Theoretical studiesand experiments were performed both for the far field (Frauhoffer zone) and the near field (Fresnel zone) of diffraction not only in the Raman-Nath regime but also for Bragg and intermediate regimes of the ultrasonic light diffraction.

Among many other achievements as a mile stones one can qualify very fundamental papers by Pieper and Korpel [78] and Chaterjee et al. [79] on strong acousto-optics interaction and the paper by Reibold and Kwiek [80,81] which analyzed the phenomenon in the very wide range of variation of Klein-Cook Q and Raman-Nath υ parameters.

It is worth mentioning about examinations related to the polarization of diffracted light beams in the ultrasonic light diffraction. Many important papers were published as for anisotropic as well as for isotropic media [15,43-46,50,64,65,82,83].

A big progress in acousto-optics in the last there decades have presented examinations which involved surface acoustic waves (SAW) enabling to shift acoustic frequences in very high range from mega to giga Hz. It has made a revolution in application of a.o. devices in integrated optical systems [49,50,51]. The whole theoretical achievements elaborated for bulk ultrasonic waves could be successfully adapted to the light and SAW interaction taking into account all the specific of the generation and propagation of SAW over the substrate, reflection and tramsmition mode of interaction etc. [16,50-52,85].

PERSPECTIVES FOR FURTHER DEVELOPMENT OF ACOUSTO-OPTICS

It is impossible in the short article to review the state of art of the topic, however as one could note from above short historical survey, some already and recently published books [15,18,45,46,50,52,53,58,84] and conference proceedings [51,54,55,57] and review articles [13,14,16,17,44,47,49,56,86] reflect the situation of the subject as of great interest and of good developed. The theoretical background for acousto-optic interaction both for the bulk ultrasonics and for the surface acoustic waves is good astablished. Two general Raman-Nath and the phase mismach systems of differential recurrence equations describe the phenomenon and can be solved for different practical cases. The vector diagrams representation is widely used in practical designing of acousto-optical devices [49,50,52,85,86]. Advances in technology have made possible to fabricate multichannal acousto-optic devices with a wide baudwidth and large dynamic range. Many acousto-optical systems have been designed for optical matrix processing, real-time ambiguity function generation for radar signals, Q - swiches and a.o. tunable filters. All these advances are important in optical signal processing. In optical communication fiber optics there are required integrated a.o. modulators, swichers, beam-forming and steering systems, optical pulse compression and optical excision and filtering systems etc. Acousto-optical devices have found application to matched filters and real-time pattern recognition using phase-only filters. The inherent parallelism of image processing as photonic signal processing gives more possibilities and better quality than electronic operational equivalents. Many other photonic devices have been designed as very fast A/D converters, optical logic gates for computing, systolic optical processors and holographic lenses for integrated interconnections [50,52,85,86]. Some recent papers presented during the 8-th Spring School on Acousto-optics and Applications joint with the 6-th AA-O'01 [55, 57] on acousto-optic bistability, chaos, and logical applications [87], on extraction and beam fanning supression using acousto-optics [88], on laserlike acousto-optic generator [89] and on elastic anisotropy of acousto-optic interaction medium [90] or on acousto-optical filter for planetary imaging and star spectroscopy [91] and on device optimization for telecommunication crossconnects [92], though arbitrary chosen, evidently show that acousto-optics have good perspectives to increase the range of its potential applications.

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