ACOUSTO-OPTICAL INTERACTIONS

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I - INTRODUCTION

When an elastic wave propagates in a transparent medium, it produces a periodic modulation of the index of refraction through the elastooptic effect. The moving phase grating may diffract a fraction of an incident light beam into one or more directions. This phenomenon is known as acoustooptic interaction.

After the original suggestion of BRILLOUIN in 1922 |1| that elastic waves would diffract light beam, experimental evidence of this effect involving thermal waves was first pointed out by GROSS in 1930 |2| then independently by LUCAS-BIQUARD |3| and DEBYE-SEARS |4| in 1932 using ultrasonic waves.

Investigations involving *incoherent* optics and sonic *coherent* waves were developed and reviews of early experiments to measure material properties and investigate the diffraction pattern under various conditions are given for instance in |5| |6|.

The scattering of light by acoustic waves is a convenient and sensitive method of investigating physical properties of crystals. Several techniques were developed to measure elastooptical and elastic constants of transparent solids. For example, in the BERGMANN-SCHAEFFER method, the sample is excited so that elastic waves propagate in many directions,setting up a grating of elastic strain. When an incident light beam illuminates the sample, the *image* of the diffracted light exhibits the elastic anisotropy of the crystal (cf. figure 1) |7|. Scattering of light by ultrasonic waves is also a very accurate method to probe the phase velocity of elastic waves |8|: In the case of figure 2 scattering of light is achieved by stationnary ultrasonic waves excited between two parallel faces of the sample. The frequencies which correspond to the resonance of the sample are detected by observing the diffraction of light between crossed polarizers

The recent development of techniques for the generation of high frequency *coherent* elastic waves, combined with the advent of laser as source of *coherent* light has given rise to a fruitful new field of research and application based on the interaction of these two coherent waves.

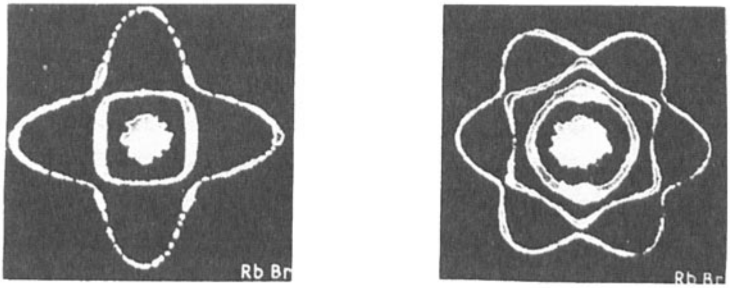


Figure 1

(a) (b)

BERGMANN -SCHAEFER diagram for Rb Br :
light propagating along
a) cubic axes, b) cube diagonals
(L. BERGMANN,Z. NATURFORSCH 12a, 229 (1957)

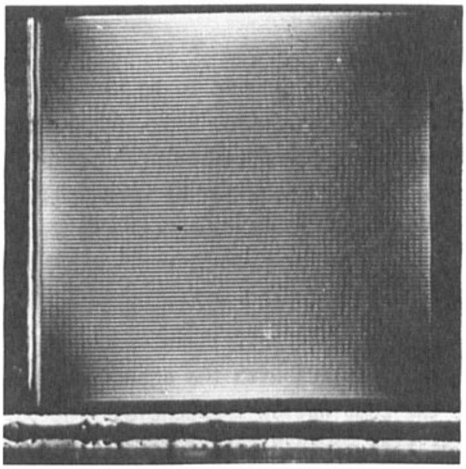
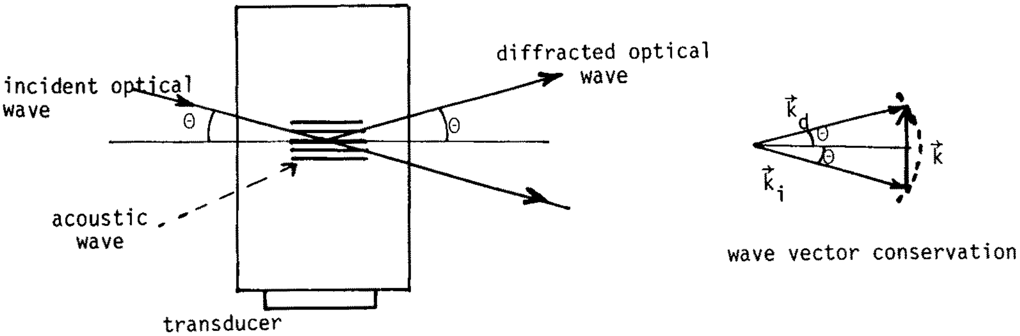


Figure 2

Stationnary ultrasonic waves in a glass sample |8|



wave vector conservation

Bragg scattering geometry in case of an isotropic material

Figure 3

More recently progress in acoustic surface waves and optical guided waves have prompted theoretical and experimental work in acoustooptic interaction in guided wave structures [9].

After a short recapitulation of the basis principle of acoustooptic interaction we give a few elementary comments about bulk wave device applications of acoustooptic interaction and then we confine ourselves to a discussion of some problems in solid state physics which are stimulated by the scattering of light by hypersonic waves.

II - ACOUSTOOPTICAL INTERACTION

Phenomenological theory of the elastooptic effect is based on POCKEL's theory which states that the change of the inverse dielectric tensor ΔB_{ij} set up by the acoustic wave is proportional to the acoustic strain S_{kl} :

$$\Delta B_{ij} = p_{ijkl} S_{kl} \qquad (1)$$

The elastooptical coefficients p_{ijkl} are generally assumed to be symmetrical with respect to ij and kl. NELSON and LAX (1970) [10] have shown this, in general, not necessarily true. They pointed out that POCKEL's formulation is incomplete and that rotation effects, arising from shear waves, should be also included in strongly birefringent media. In place of the acoustic strain, one must use the displacement gradient as the pertinent variable.

Acoustooptic diffraction can be represented as a parametric interaction [11]. Via the elastooptic effect, the incident optical wave mixes with the acoustic waves to generate a number of polarization waves at the combination frequencies. The polarization waves in turn will generate optical radiation at these new frequencies.-provide that phase matching between these two waves is achieved-. In general multiple diffraction to higher orders may occur, if the interaction length L is sufficiently large however light intensity in the high diffraction orders become negligibly small.

Multiple diffraction to higher orders (RAMAN-NATH regime) occurs providing that L is smaller than the critical interaction length $L_c = \frac{n \Lambda^2}{\lambda_0}$. This limit is increasingly difficult to satisfy according to simultaneous increase in the acoustic frequency. For instance in fused silica for $\lambda_0 = 0,633$ µm, $L_c = 8,4$ mm at 100 MHz and $L_c = 0,93$mm at 300 MHz. Thus L_c is approximately the minimum interaction length to insure that the diffraction occurs in the BRAGG regime.

Typical arrangement to perform acoustooptic interaction is shown figure 3. Ultrasonic waves are generated into a material medium (usually a solid) by means of a piezoelectric transducer bonded to one face of the sample. With well enough collimated optical and ultrasonic beams it is possible to set out the geometry so that the amplitude of the light scattered by adjacent volumes adds constructively and scattering is obtained for a *single* angular phase matched direction.

In case of infinite plane wave the interaction process conserves the momentum and the energy :

$$\vec{k}_{\text{diffracted}} = \vec{k}_{\text{incident}} \pm \vec{K}_{\text{acoustic}} \qquad (2)$$

$$\omega_{\text{diffracted}} = \omega_{\text{incident}} \pm \Omega_{\text{acoustic}} \qquad (3)$$

With regard to the small difference in frequency between the two optical waves (the acoustic frequency beeing small compared to the optical)- the locus of the scattering interaction in momentum space is a circle with radius k. So in case of isotropic medium we obtain the condition :

$$\text{Sin}\,\Theta_B = \frac{1}{2}\,\frac{|\vec{K}|}{|\vec{k}|} = \frac{\lambda_o}{2\,n\,\Lambda} \qquad (4)$$

Λ acoustic wavelength
λ_o free space optical wavelength
n index of refraction of the material

This is named "BRAGG condition" by formal analogy with XR diffraction by lattice planes. Furthermore it can be pointed out that the intensity of the diffracted light beam depends on the acoustic intensity. In particular for low acoustic power the intensity of the diffracted beam is proportional to the acoustic power. Furthermore the ability of a material to diffract lightbeam depends on its figure of merit :

$$M = \frac{p^2\,n^6}{\rho\,V^3}$$

p : effective photoelastic constant
ρ : density
V : acoustic velocity

III - DEVICE APPLICATIONS

We can expect from the previous considerations that acoustooptic interaction is very convenient for the design of devices intended to perform various optical beam control functions |11| |12| |13|. These basic acoustooptic devices are characterized by three distinct regimes of interaction geometry depending on the parameter $a = (\frac{\delta\,\Theta_o}{\delta\,\Theta_a})$, the ratio of divergence angles of the optical beam and the acoustics beam.

In the limit $a \ll 1$, the device acts as a deflector, for $a \sim 1$ as a modulator and in the limit $a \gg 1$ it can be used as an optical filter.

We discuss here deflector and modulator functions

- Deflector :

From (4) we can expect that the direction of the diffracted beam can be varied by changing the driving frequency. In a deflection system the main parameters are resolution and speed. Resolution is defined as the range of deflection angles divided by the angular spread of the diffracted beam :

$$N = \frac{\Delta \Theta_B}{\delta \Theta_B} \qquad (5)$$

Where from (4) the total angle of deflection for a frequency change Δf is :

$$\Delta \Theta_B = \frac{\lambda_0 \Delta f}{n V \cos \Theta_0} \qquad (7)$$

(V : acoustic wave velocity)

In the limit $a \ll 1$, the divergence of the diffracted beam is equal to that of the incident beam. Resolution N is proportional to $\tau \Delta f$, where τ is the acoustic transit time across the optical beam. τ is also a measure of the speed of the deflection system. So the deflector bandwith Δf which is proportional to the resolution and speed product is the main parameter to characterize the efficiency of the deflector.

The first application of an acoustooptic deflector was the horizontal deflection in a laser TV display |14| . The discovery of new efficient acoustooptic materials such as $PbMoO_4$ and TeO_2 allowed to increase the deflector bandwith significantly (150 to 300 MHz) with a resolution of about 1000 spots. A good review of main applications of acoustooptic deflectors is given for instance in ref |11|.

- Modulators :

The acoustooptic interaction may also be used to modulate light. Both amplitude and frequency modulators can be achieved. For proper modulator operation, the divergence of the optical beam must be about equal to that of the acoustic beam : $a = \frac{\delta\Theta_0}{\delta\Theta_a} \sim 1$

Scattering with amplitude modulated acoustic frequency removes energy from the incident light beam and produces an amplitude modulated scattered beam.

The requirement of equal diffraction angles is necessary to assure the full use of all the acoustic and optical energy.

The success of acoustooptic modulations increases in recent years due to their many advantages such as low drive power, high extinction ratio (ratio between the maximum intensity of the diffracted laser beam) all types of modulation available...

Design and construction of a acoustooptic modulator for communication in the infrared is reported for instance in |15|, |16|.

Another fruitful field of applications is the use of acoustooptic modulator inside a laser cavity. These intra cavity application involve Q-Switching, mode locking and cavity dumping.

In some TV experiment deflector and modulator are associated |17|.

IV - ACOUSTOOPTIC INTERACTION AS LOCAL PROBE TO STUDY THE PHYSICAL PROPERTIES OF TRANSPARENT MEDIA.

From the previous considerations (cf § 2), we can expect that the scattering of light by elastic waves is a convenient and sensitive investigation method of some physical properties of transparent media.

a - The BRAGG angle is proportional to the ratio of elastic wave frequency to velocity. This proportionality can be used to measure the velocity.

b - The intensity of the diffracted light is proportional to the acoustic intensity which provides a probe of the acoustic intensity within the sample and consequently of the attenuation of hypersonic waves...

c - Measurements of the diffraction efficiency can be used to determine elastooptical coefficients of materials.

d - The phase shift of the diffracted light can be used by mixing with the undiffracted light to probe the phase of the elastic wave.

In an other way scattering of light by coherent elastic waves (BRAGG scattering) is very complementary of scattering of light by thermal waves (BRILLOUIN scattering).

These thermal waves grow spontaneously, oscillate at the sound frequency Ω (k) and decay away at a charateristic rate Γ (k) only to be replaced by another wave with a different starting phase and a similar temporal history |18|, |19|. The spectrum of the scattered light, deriving from correlations in the fluctuations in the thermal phonons, consists of a pair of doublets, whose shape is Lorentzian if the correlation function for the sound wave amplitude dies off exponentially. The width of the spectral lines gives the sound waves lifetime $1/\Gamma$ (k) and the splitting of the doublets around the unshifted frequency is equal to the frequency of the scattering sound wave :

$$\frac{\Omega}{2\,\Pi} = \frac{V}{\Lambda} = \frac{2\ V\ n}{\lambda_o}\ \sin\frac{\Theta}{2}$$

(Θ is the angle between the incident and the diffracted light beam) Thus the scattering angle Θ determines the wavelength of the scattering sound wave. By scattering through larger and larger angles sound waves of shorter and shorter wavelength are probed.The shortest sound wave responsible for light scattering being equal to one half the wavelength of the light in the medium.

Until the advent of laser, the breadth of the spectrum of the incident light made it difficult to resolve the BRILLOUIN doublets and almost impossible to determine their natural linewidth. The use of laser as monochromatic, intense and unidirectional light source gives a review of interest for this technique and in conjunction with high resolution spectroscopy its allows to determine the velocity and attenuation of sound waves whose frequency may be as high as 20-30 GHz (in case of back-scattering)

We want now exemplify by a choice of some problems in the domain of solid state physics the importance of acoustooptic interaction as local probe to study the physical properties of transparent media.

1) Phonon-phonon interaction

Experimental studies of the hypersonic attenuation in crystals and its dependence on the frequency are important from the standpoint of the theory of phonon-phonon interaction. In case of BRAGG scattering, the measurement of the diffracted light intensity as a function of the distance to the transducer allows to obtain the *intrinsic* attenuation in the crystal getting rid of spurious effects such that due to the bonding of the sample or the non parallelism of its faces that can occur in classical pulse-echo techniques that provides a *transit time* in the sample.

From the previous considerations BRAGG scattering used in conjunction with BRILLOUIN scattering is a very convenient method to probe in a wide range of frequency (typically 100 MHz to 30 GHz) the attenuation of elastic waves [19].

2) Phase transitions

Another especially promising application of light scattering by elastic waves is the study of crystals which experience phase transition [20]. It can be used for instance to investigate the critical phenomena occuring in the vicinity of phase transitions such as domain structure, interaction of acoustic waves with domain walls. Damping and velocity of elastic waves may be simultaneously measured near the phase transition. The possibility of carrying out measurements over displacements of the order of 1 mm inside a domain of the crystal allows first to determine the high value of the attenuation and, second practically to eliminate the effect on the results of temperature gradients.

3) Acoustic activity

Another facinating problem is the phenomenon of acoustic activity which is the mechanical analogy of optical activity. Acoustic activity is related to the spatial dispersion of the elastic moduli :

$$C_{ijkl}(\Omega, \vec{K}) = C_{ijkl}(\Omega) + i\,\gamma_{ijklmn}(\Omega)\,K_m + \dots$$

The acoustic gyrotropy tensor γ lifts the degeneracy for transverse elastic waves at finite wave vector. In case of quartz crystal the effect was previously exhibited in neutron scattering results [22] and by BRILLOUIN scattering [23].

The acoustic activity was also measured directly by classical ultrasonic experiments [24] [25]. Experiments of this kind yield results that are averaged over the entire length of the crystal. Acoustic activity in quartz crystal was investigated by means of BRAGG scattering [26] along the Z axis of a quartz crystal. The intensity of the scattered light oscillates with a period which depends of the specific rotation ability of the crystal. So it is possible to probe the effects of gyrotropy at arbitrary points of the sample.

4) Characterization of the local homogeneity of sample.

We refer now to the use of light scattering by acoustooptic interaction to obtain both the amplitude and the phase of the ultrasonic wave as is propagates in the sample.

The phase of the elastic wave may be detected by beating the diffracted field with a reference (a fraction of the incident undiffracted light beam). By translating the sample continuously in the same direction as the acoustic wave vector $\vec{K}$, the beating signal changes sinusoidally to give both the amplitude and the phase of the elastic wave. The device described in reference|27| allows to measure the acoustical wavelength in the frequency range 200 MHz - 1 GHz with a spatial resolution of the order of 10 µm. By means of this device, local ultrasonic velocity fluctuation of the order of 10^{-4} can be detected. Thus, applications such as control of material doping (homogeneity, impurity gradients etc...) and fundamental studies of phonon propagation in thermal or strain gradients may be anticipated.

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