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The Influence of Surface and Volume Effects on the Light Diffraction by SAW at Parallel Interfaces

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Abstract. The paper deals with the results of numerical calculations and experiments concerned with the contribution, due to the surface rippling and fluctuations of the refractive index in the layer closest to the surface, to the light diffraction by surface acoustic waves (SAW). The analysis includes all basic types and geometries of parallel interaction taking as an example DADP crystals.

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The light diffraction by SAW depends mainly on the geometry of interaction, the SAW type and the kind of medium in which it occurs. In relation to the geometry there may be distinguished the following basic types of interaction: – parallel – when the wave vector SAW **K** lies in the plane of light incidence, – perpendicular – when **K** is perpendicular to the plane of light incidence. In each of these types, light diffraction is possible in case of: external reflection (ER), internal reflection (IR) and light transmission (TR) from/by the surface on which SAW is propagating. The efficiency of diffraction is also dependent on the polarization of light, the incident angle, and the plane and direction of SAW propagation. The aim of this paper is to investigate how the change of each of the above mentioned factors affects the contribution of surface, and close to surface, layers in the light diffraction by SAW propagating in deuterized crystals of the antiferroelectric type $NH_{4(1-x)}D_{4x}H_{2(1-x)}D_{2x}PO_4$.

1. Theoretical Outline

Theoretical studies of light diffraction by SAW were started in the mid seventies. They were limited to particular, materials and geometry of interaction [1–6]. The method applied to our investigations allows us to analyse this complex phenomenon in any

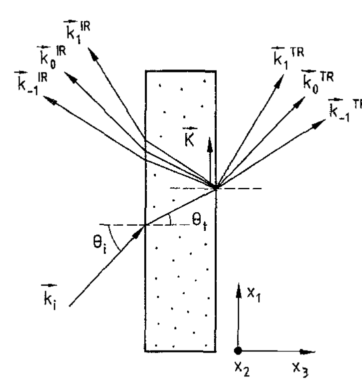

Fig. 1. Geometry of the interaction between a SAW and light

material and any geometry of interaction. We have assumed a parallel geometry of interaction of an electromagnetic waves and SAW, as shown in Fig. 1. The analysis has been carried out in the reference system $x_1x_2x_3$, referred to as the wave system. It has been chosen in such a way that the axis x_1 would be parallel to the vector **K**, and the axis x_3 parallel to the normal vector **n** to the surface of SAW propagation. Let us assumed that on the surface of a piezoelectric crystal SAW propagates, given by [7, 8]

$$u_i(x_1, x_3, t) = \sum_{n=1}^{4} u_i^{(n)} \exp[iK(x_1 + l_3^{(n)} x_3 - vt)], \quad (1)$$

where $u_i^{(n)}$ denotes the normalized amplitudes of partial waves, $l_3^{(n)}$ the decay constants, u_1, u_2, u_3 the displacements components of the medium, and u_4 the electrical potential in the medium.

This wave causes the rippling of the surface and periodic fluctuations of the refractive index in the layer whose thickness equals the depth of SAW penetration due to elasto- and electrooptical effects. Depending on the type of interaction, each of them contributes to the diffracted fields. In case of external reflection from SAW, the light diffraction occurs on the surface ripplings. In case of light transmission or internal reflection however, the light diffraction occurs on the ripplings of surface and the fluctuations of a refractive index. The efficiency of diffraction thus, in a general case, may be expressed as a superposition [1–3]:

$$\eta_{(\Theta_i)}=\left(\frac{2}{k_i u_{30}}\right)^2 \frac{I_1}{I_0} \sim |Z_{1(\Theta_i)}+V_{1(\Theta_i)}|^2\,, \tag{2}$$

where k_i is the wave number incident electromagnetic wave, $u_{30}=u_3\,\widehat{(x_3=0)}$, I_0, I_1 the intensity of the incident and diffracted light in beam of 1st order, $Z_{1(\Theta_i)}$ normalized function describing the contribution of the rippled surface to the diffracted electromagnetic wave, and $V_{1(\Theta_i)}$ normalized function describing the elasto- and electrooptical contributions to the diffracted fields.

The light diffraction by SAW in the investigated group of crystals is regarded as the diffraction of Raman-Nath's type up to the frequency range of several hundred MHz. Assumed that $K/k_i \ll 1$, $k_i u_{30} \ll 1$ ables us to determine the functions $Z_{(\Theta_i)}$, $V_{(\Theta_i)}$ in each type of interaction. The solutions are:

$$Z^{\mathrm{ER}}_{1(\Theta_i)}=2\cos\Theta_i\,, \tag{3}$$

$$Z^{\mathrm{ER}}_{1(\Theta_i)}=2n\cos\Theta_i\,, \tag{4}$$

$$Z^{\mathrm{TR}}_{1(\Theta_i)}=n\cos\Theta_t-\cos\Theta_i\,, \tag{5}$$

$$V^{\mathrm{TR(s)}}_{1(\Theta_i)}=-\frac{1}{2}\frac{n_0^3}{iK\cos\Theta_t}\sum_{n=1}^{4}\Delta B_2^{(n)}\frac{1}{l_3^{(n)}+\mathrm{tg}\,\Theta_t}\,, \tag{6}$$

$$V^{\mathrm{TR(p)}}_{1(\Theta_i)}=-\frac{1}{2}\frac{n^3}{iK\cos\Theta_t} \times\sum_{n=1}^{4}(\Delta B_1^{(n)}\cos^2\Theta_t+\Delta B_3^{(n)}\sin^2\Theta_t-\Delta B_4^{(n)}\sin 2\Theta_t) \times\frac{1}{l_3^{(n)}+\mathrm{tg}\,\Theta_t}\,, \tag{7}$$

where

$$\Delta B_j=iK(p_{j1}+p_{j5}l_3^{(n)})\,u_1^{(n)}+(p_{j6}+p_{j4}l_3^{(n)})\,u_2^{(n)} +(p_{j5}+p_{j3}l_3^{(n)})\,u_3^{(n)}-(r_{j1}+r_{j3}l_3^{(n)})\,u_4^{n}\,,$$

p_{jl}, $r_{j\alpha}$ are the elasto- and electrooptic constants

(j, $l=1,\ldots 6$; $\alpha=1,\ldots 3$,);

in (4, 5, 7),

$n=n_0$ for the perpendicular light polarization (s), $n=n_0-(n_0-n_e/n_e)\sin^2\Theta_i$ for the parallel light polarization (p).

In case of the internal light reflection from the surface of SAW propagation, the light passes twice through the layer closest to the crystal surface in which there occur the periodic fluctuations of the refractive index. Thus the total coefficient of diffraction efficiency for the first-order beams may have the following form:

$$\eta^{\mathrm{IR}}_{(\Theta_t)}=(1-R^2_{(\Theta_t)})\,(1-R^2_{(-\Theta_t)})r^2_{(\Theta_t)}|Z^{\mathrm{IR}}_{(\Theta_t)}+V_{(\Theta_t)}+V_{(-\Theta_t)}|^2\,, \tag{8}$$

where $R_{(\Theta_t)}$, $r_{(\Theta_t)}$ the coefficient of electromagnetic-wave reflection from the free and metalized crystal surface. The calculations of each contribution and of the total efficiency of the light diffraction may only be performed by numerical means, due to the complex nature of the problem.

2. The Results of Numerical Calculations and Experiments

Numerical calculations are possible only when we know all the components of the six following tensors: elastic, piezoelectric, dielectric for low and optical frequencies, elastooptical and electrooptical. In the first stage of calculations we must determined all the parameters which characterize the SAW, i.e. the propagation velocity v, four constants of decay $l_3^{(n)}$, sixteen normalized amplitudes of partial waves $u_i^{(n)}$. The results of these calculations for the group of crystals under investigation are shown in [9]. Next, we have to calculate the contributions $Z_{(\Theta_i)}$ and $V_{(\Theta_i)}$ and the efficiency of the light diffraction $\eta_{(\Theta_i)}$. Due to normalization by u_{30}, the function $Z_{(\Theta_i)}$ are real but $V_{(\Theta_i)}$ may be complex. Thus, it may be concluded that the intensity of the diffracted light depends to a large extent on the relative phase of the diffracted fields components. Examples of results are shown in Figs. 2–4. The results refer to all basic types of interaction in case when SAW is propagating in the direction ⟨100⟩ on the plane (001) of the crystal $NH_4H_2PO_4$. For comparisons, each figure includes the results for both basic types of light polarization (s and p). The measurements were made using the acoustooptical experimental arrangements, shown earlier [10], for SAW of frequency 49 MHz. The applied method of transmitting an elastic wave from the $LiNbO_3$ plate onto the examined surface enabled us to transmit it in any optionally chosen direction. The methods applied to our experiments were discussed in more detail in [11]. These method allowed to carry out measurements independently of the coupling value of SAW transmission and various disturbances. Compliance with all the

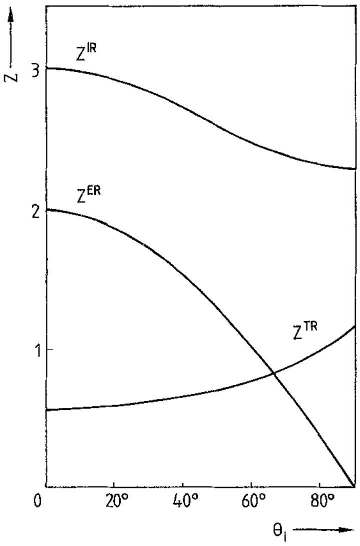

Fig. 2. Contribution the rippling of the surface to the light diffraction efficiency vs. Θ_i in the cases ER, IR, TR

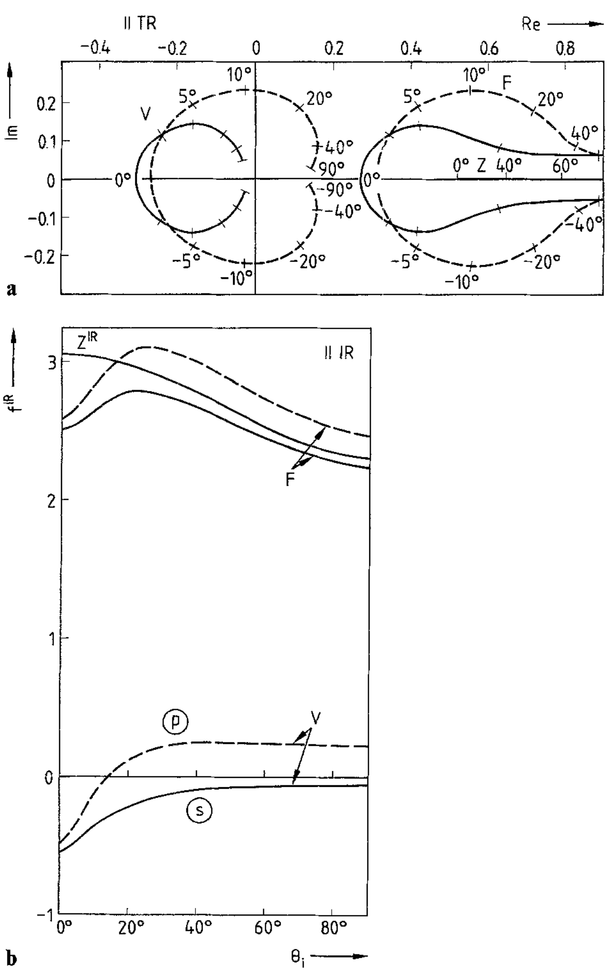

Fig. 3. Light diffraction in the cases a (light transmission) and b (internal reflection of the light) [Z: surface, V: internal, F: total contributions; s: polarization (solid line), p: polarization (dashed line)

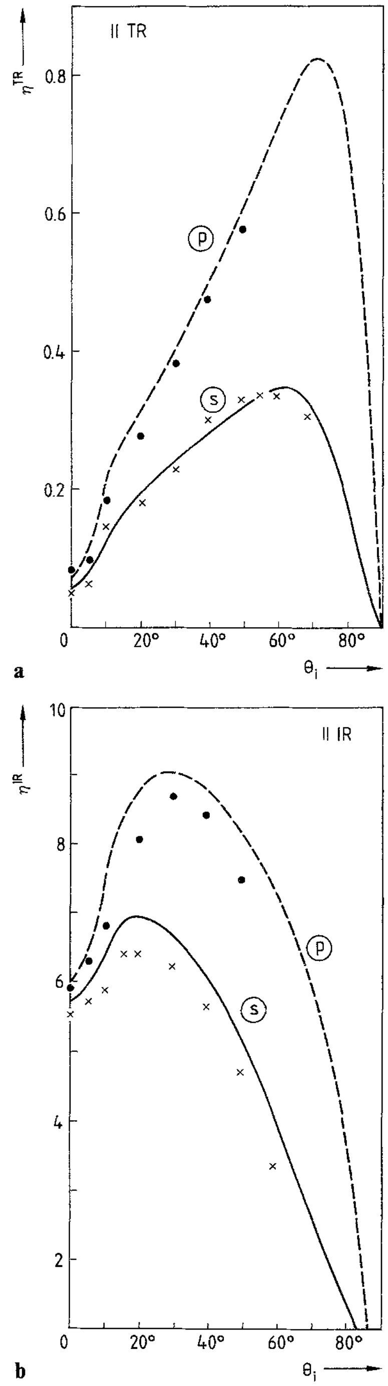

Fig. 4. Light diffraction efficiency vs. Θ_i in the cases a (light transmission), and b (internal reflection of the light)

assumptions referring to theoretical formulae was ensured in the experiments. The results of measurements have been pointed out in the figures.

3. Discussion

An analysis of the results allows us to draw a number of interesting conclusions, concerning the quantity and

Table 1

Efficiency of diffraction	Θ_i
$\eta^{TR(s)} < \eta^{TR(p)}$	[0°, 90°]
$\eta^{IR(s)} < \eta^{IR(p)}$	[0°, 90°]
$\eta^{IR(s)(p)} \gg \eta^{TR(s)(p)}$	[0°, 90°]

Table 2

Type of interaction	$\Theta_{i\max}$	$\Theta_{i\min}$
ER (s)	0°	90°
ER (p)	0°	Br and 90°
TR (s)	~60°	0° and 90°
TR (p)	~70°	0° and 90°
IR (s)	0° or ~20°	90° sometimes 0°
IR (p)	0° or ~27°	90° sometimes 0°

phase of particular contributions to the field diffraction as well as the relations and changes in the function of light diffraction efficiency in particular types of interaction. It was concluded that the contribution due to the surface effect depends only on the type of interaction (ER, IR, TR) and the angle of interaction Θ_i, it is only slightly affected by the changes of other factors (e.g., light polarization, the plane and direction of SAW propagation). The periodic fluctuations of the refractive index contribute to the elasto- and electrooptical effects in the layer closest to the surface; they depend mainly on the type, kind and angle of interaction, the polarization of incident light and the plane and direction of SAW propagation. In the case when $V_{(\Theta_i)}$ is a complex function, both its quantity and phase are changed. It has been proved that in the investigated group of crystals there occur the following relations between contributions:

$$Z^{IR}_{(\Theta_i)} > Z^{ER}_{(\Theta_i)} > Z^{TR}_{(\Theta_i)} \text{ for } 0° \leq \Theta_i < 65°,\ Z_{(\Theta_i)} > |V_{(\Theta_i)}| \text{ for } 0° \leq \Theta_i < 90°,\ |V^{IR}_{(\Theta_i)}| > |V^{TR}_{(\Theta_i)}| \text{ for } 0° \leq \Theta_i < 10°,\ |V^{TR(p)}_{(\Theta_i)}| > |V^{TR(s)}_{(\Theta_i)}|\ 5° \leq \Theta_i < 90°\,.$$

The relations between the quantities of light diffraction efficiency for particular types of interaction shows Table 1.

Table 2 containts the values of incidence angles for which the light diffraction efficiency reaches maximum or minimum for the basic geometries of interaction. It turned out that in case of ER, the diffraction occurred only on the surface ripplings. On waves of Bleunsteina-Gulyaeva, the light diffraction may take place only in cases of TR and IR, and the only contribution is due to the volume effect. In a general case, however, the contribution due to the volume effect may be partially changed by changing the geometry of interaction and metallization of the propagation surface in case of IR.

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