Optical radar processor:

Part I. Theoretical considerations concerning processor elaboration

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The paper is divided into two parts. In the first part, the advantages resulting from the application of optical processors in microwave radars were presented and theoretical considerations performed. Then, realisation of the optical radar processor based on the own concept, is presented. The second part of the paper presents the structure, purpose, technology and experimental examinations of the optical processor.

1. Introduction

The development of radiolocation is inspired by developments in many disciplines of science and technology. Significant changes in the quality of the contemporary radars are connected mainly with new developments in solid state technology, mathematics, information technology and optics. The progress in solid state technology has accelerated the scaling down of radars, improved durability, and enabled new applications to be found for them. The progress in applied mathematics enabled, among others, a change in the approach to spectral analysis of signals, to filtration issues and detection methods. Introduction of information technology enabled digital processing of radar signals, improved the quality of secondary processing and besides it increased the precision of operation of radar control devices. Research on optical systems implementation in microwave radars indicates the development direction in the field of radiolocation. It includes, at the present stage, research on three groups of subjects, i.e. radar antenna arrays, optical signal processing in active radars with passive response, signal processing in radioelectronic recognition radars.

Optoelectronic shaping of characteristics and controlling of radar antenna arrays ensures a very good beam shape, high precision control and design simplicity. Such solutions are approximately 10 times lighter than conventional ones, remaining totally resistant to interference, even in the case of electromagnetic pulse occurring during thermonuclear explosion [1]. They may be used in ground radars with a large antenna network, in aircraft deck radars and in spacecraft radars.

Systems for the optical processing of radar echo signals feature high operation speed. Relatively easily, they enable the realisation of multichannel and multifunction signal processing in real time, as well as obtaining their various two-dimensional

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transformations. In optical filters any phase-frequency characteristic may be obtained relatively easily and can be changed easily, if necessary. The circuits may be applied in various types of radar. The widest possibilities of their application are envisaged for radars with phased antenna arrays [2].

Application of optical signal processing in radioelectronic recognition radars is particularly valuable since it enables simultaneous processing of large portions of information in a small device. For all three types of application of the optical methods, mentioned above, a circuit called "optical radar processor" may be identified. Generally, it consists of a laser, laser light modulator (controlled by a radio signal), optical transforming system and a set of photodetectors or input fibre optics terminals.

The purpose of this paper is to elaborate and examine experimentally such a processor. Since at the present stage of radar development it is not possible to make one device, which could be used in all three modes mentioned above, it was assumed, that some subassemblies of the processor may be exchanged.

2. Basic applications of radar optical processors

2.1. Optoelectronic control of radar antenna array beam

Development of the MMIC technology (monolithic microwave integrated circuit) created the possibility of applying phased antenna arrays in aircraft and spacecraft. The necessity arose to develop light, precise and reliable systems for forming antenna characteristic and beam controlling. It was determined [1, 3–5], that optical processors are the most appropriate for this purpose, while their application could be extended onto big antenna arrays (phased antenna networks) in ground radars.

Optoelectronic control of radar antenna array beam is realised by means of optical processors equipped with acousto-optical laser light modulators (Fig. 1).

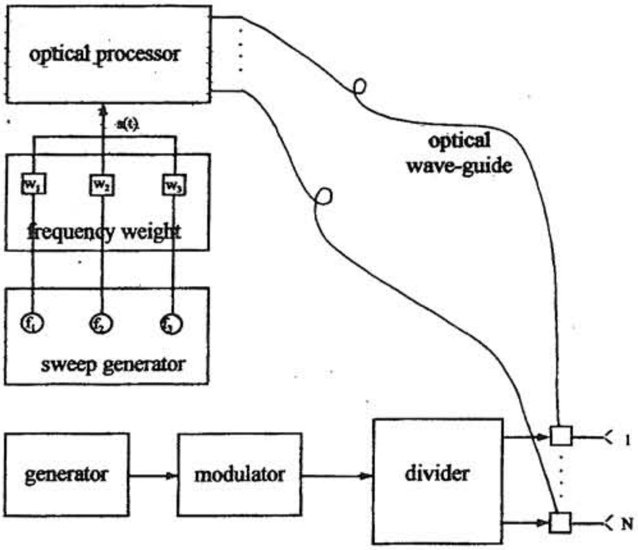

Fig. 1. Optoelectronic beam control.

Modulator operation is controlled by a properly shaped radio signal s(t). As a result of the Bragg diffraction (Fig. 2), behind the transforming lens light signals are obtained which respond to spectral structure of the radio control signal s(t). In the focal plane of the lens, the obtained light signals are introduced into glass fibres, which bring them to the phase shifters of the antenna array.

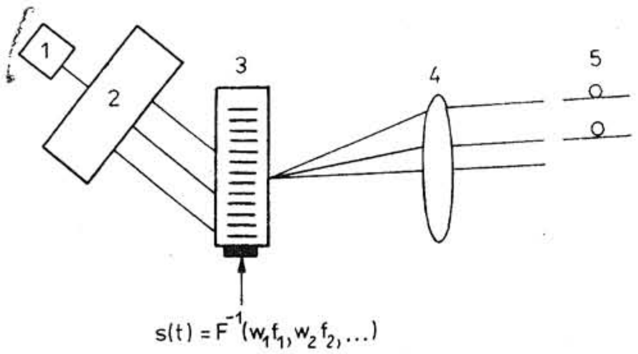

Fig. 2. Optical processor [1] controlling antenna array radar beam: 1 – laser, 2 – collimator, 3 – laser light acousto-optical modulator, 4 – transforming lens, 5 – optical fibres

2.2. Optical processing of the radar echo signals

An optical processor, similar to the one presented in Fig. 2. constitutes the basic optical part for optical processing of the echo signal in the active

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microwave radar with a passive response [6]. The acousto-optical modulator of the laser light is controlled by the radio signals reflected by a target object. Depending on the modulator parameters and on the operational frequency of the radar, they are led into the modulator directly from the antenna, or after conversion. Optical signal processing brings the biggest advantages in radars equipped with antenna arrays [7]. Fig. 3 presents a simplified structure of the optical processor to be used in a radar with a linear antenna array. The acousto-optical light modulator is a multistage structure here. Each stage of the modulator is connected to the respective element of the antenna array. In the "z" axis of the coordinate system the situation of the lens plane is shown as well as the spectral plane situated 2 focal lengths from the origin of the coordinates. A collimated laser light beam, after passing through the modulator, constitutes an optical equivalent of the radio echo signal. In the spectral plane, according to the light intensity distribution, along the abscissa axis, values of the angular coordinate of the target object is read. and along the ordinate the carrier frequency of the echo pulses is determined. Accordingly the Doppler frequency shift of the carrier frequency, radial frequency of the object is determined. The time after which the light signals appear in the spectral plane is proportional to the distance from the object.

The optical processors may also be applied in radars equipped with circular antenna arrays and in radars with two-dimensional antenna networks. For all solutions mentioned above (e.g. Fig. 3), the respective dimensions of the modulators are smaller (approx. 10^{-3}) with respect to the actual dimensions of the antenna arrays from which the control signals are coming.

2.3. Signal transformation in radioelectronic recognition radar

Through the application of optical processors in passive radars for radioelectronic recognition (Fig. 4), dimensions and design costs are reduced, reliability is increased and simultaneous estimation of the parameters of a large number of radar signals is ensured, in a wide range of frequencies [8, 9]. It creates the possibility of increasing quality and efficiency of recognition, as well as the possibility of developing radioelectronic recognition units outside the professional recognition units. In the latter case, optical processors ensure that such military objects as aircraft and ships may be equipped with cheap indicators of microwave radiation reception and warfare on a tactical level. Besides, optical processors may be applied in "our/enemy" aircraft recognition systems, to examine parameters of noise signals and in direction-finders.

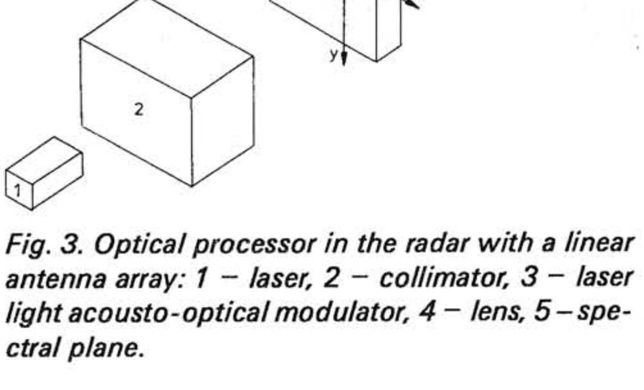

Fig. 3. Optical processor in the radar with a linear antenna array: 1 – laser, 2 – collimator, 3 – laser light acousto-optical modulator, 4 – lens, 5 – spectral plane.

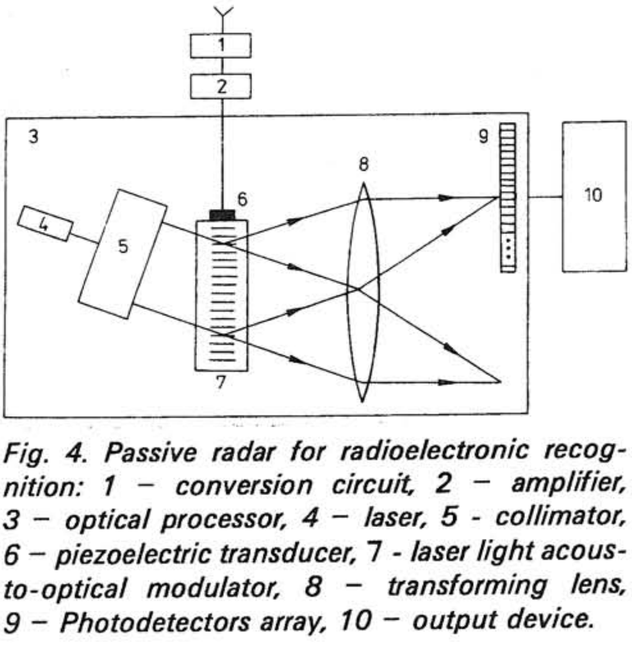

Fig. 4. Passive radar for radioelectronic recognition: 1 – conversion circuit, 2 – amplifier, 3 – optical processor, 4 – laser, 5 - collimator, 6 – piezoelectric transducer, 7 - laser light acousto-optical modulator, 8 – transforming lens, 9 – Photodetectors array, 10 – output device.

3. Preferable solutions

In the research centres investigating optoelectronic systems for microwave radiolocation two trends are observed on implementation of newly elaborated solutions. The first consists in the modernisation of contemporary radars. This is achieved by adding an optical processor to the radar design in order to widen the variety of radar capabilities. Also, the changing of a signal processing unit into an optical processing system is performed in order to increase the quality of detection and estimation of target parameters. Sometimes, both types of modernisation are applied simultaneously. The second trend of optoelectronics introduction into practical solutions assumes the elaboration a new generation of microwave radars just from the rudiments, with the application of the whole variety of optical solutions, including the implementation of optical computers for data processing.

In general, the research is at the laboratory stage. Among the practical applications used at present, one should mention the aircraft radars for side observation with an optical signal processing and synthesised antenna aperture. Besides, volume production of passive recognition radars may use systems for optical processing [9].

The development of optical processors is accompanied by circuit integration. Significant progress in integrated optics promotes this development. Nevertheless, not all types of optical processors may be obtained as fully integrated. The reason being the increasing requirements for control signal power, as well as the purpose and the level of complexity of the processor optical system.

4. Considerations preceding elaboration of the processor

4.1. System concept

Earlier papers [2, 9-13] contributed substantially to the development of the concept of optical processing of radar signals with the use of spectral analyser. According to the present tendency in optoelectronics development, the processor should be built using exclusively, or at least partially, integrated optics. The radio signal should be transformed into its optical equivalent by an acousto-optical light modulator, based on the planar fibre optic device, several micrometers thick. In order to achieve high operating efficiency of the modulator, the energy of the acoustic wave should be concentrated in the base layer of a similar thickness (so called, field overlapping). Besides, the condition of the acoustic wave excitement should be technologically easy. These conditions are fulfilled by the Rayleigh acoustic surface waves.

Detection of particular components of the spectrum should be realised by placing a photodetectors array in the spectral plane of the output lens. Each element of the photodetector array will give a response directly proportional to the amplitude of a spectrum component, while the channel number in the line will determine the spectrum frequency.

Development of the structure described above is a basic variant, the functions of which could be expanded by developing the output optical part of the system.

A practical application of this solution is proposed in the form of receivers of passive radars used for radioelectronic recognition and separate adapters for active radars with a passive response.

4.2. Acousto-optical interaction in planar circuits

According to the adopted concept of the system, an acousto-optical light modulator with a planar fibre optic element is the key component of the processor. In order to ensure an adequate structure of the modulator, the interaction between the acoustic wave and the processed light wave should be considered. It will enable the selection of a proper diffraction type and the right incidence angle of the input laser light beam. For further considerations a diffusion waveguide is assumed (Fig. 5), made of $LiNbO_3$ single crystal doped with titanium. Diffusion of Ti into $LiNbO_3$ will cause changes in the dielectric permittivity of the crystal as well as in the refraction index.

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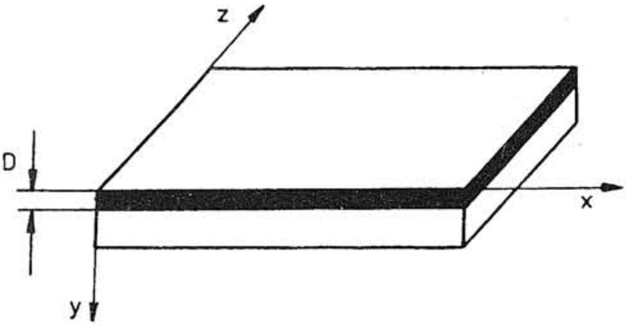

Fig. 5. Diffusion waveguide: D – diffusion depth.

A change in the refraction index can be described by the Gaussian function or the erfc function (Fig. 6).

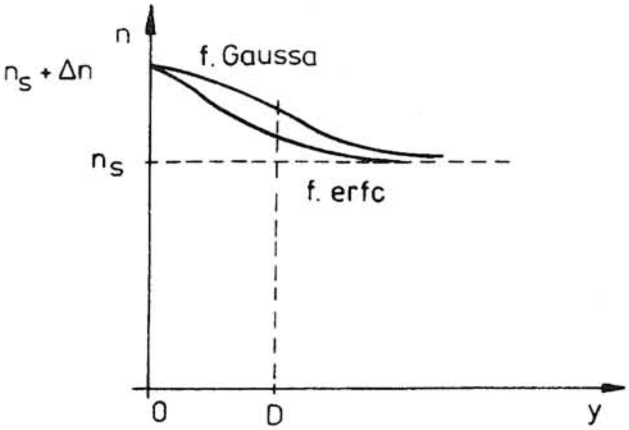

Fig. 6. Refraction index change described by the Gauss function and erfc function.

The distribution of the refraction index versus the Ti concentration may be determined as follows:

$$n(y) = n_s + B\,C(y,t) = n_s + B\,\frac{N_o}{(\pi + D)^{1/2}} \exp - \left[\frac{y^2}{4tD_x}\right] \qquad (4.1)$$

$$D = (4\,t\,d_x)^{1/2}$$

where:

$C(y,t)$ – Ti concentration

B – Coefficient

N_o – Number of diffused atoms in the initial state

t – Diffusion time

D_x – Diffusion coefficient

The penetration depth of the acoustic wave is inversely proportional to the control signal frequency. The share of acoustic surface waves in the operation of the light modulator is determined by changes in the dielectric permittivity of the crystal [15]:

$$\Delta\varepsilon_{rs} = -\,\varepsilon_{ri}\,(p_{ijkl}\,S_{kl} + r_{ijk}\,E_k^{(a)})\,\varepsilon_{js} \qquad (4.2)$$

where:

ε_{ij} – components of dielectric permittivity;

p_{ijkl} – photoelastic coefficients

r_{ijk} – electrooptical coefficients

S_{kl} – components of deformation field

$E_k^{(a)}$ – components of electric field

The determination of the distributions of shifts $S_{kl}(y)$ and $E_k^{(a)}(y)$ enables the analysis propagation of surface acoustic waves in the XZ crystal plane (Fig. 5) and selection of an optimum direction in their interaction.

The division of acousto-optical interaction in planar structures is carried out upon the propagation direction of optical or acoustic waves, as well as on the basis of the mutual relation between parameters describing these waves. The following interactions are considered: Raman-Nath interaction, Bragg and collinear interactions (Fig. 7). For all these interactions the relation between vectors and frequency is binding:

$$\begin{aligned}\vec{\beta}_d &= \vec{\beta}_i \pm \vec{K}\\ \omega_d &= \omega_i \pm \Omega\end{aligned} \qquad (4.3)$$

where:

$\vec{\beta}_i$ – wave vector for the incident wave;

$\vec{\beta}_d$ – wave vector for the diffracted wave;

$\vec{K}$ – wave vector for the acoustic wave;

ω_i – pulsation of the incident wave;

ω_d – pulsation of the diffracted wave;

Ω – pulsation of the acoustic wave.

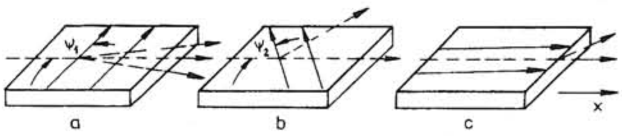

Fig. 7. Types of acousto-optical interaction: a – Raman-Nath $\Psi_1 = 90°$, b – Bragg, $\Psi_2 = 90° - \Theta_B$, Θ_B – Bragg angle, c – colinear

For the particular frequency of the surface acoustic wave, the above relations (4.3) are fulfilled in a certain range of incident and diffraction angles. From a practical point of view, the most interesting is the Bragg and Raman-Nath interaction. The Bragg interaction features very high efficiency of the interaction of waves (theoretically up to 100%). It is advantageous that only one diffraction order occurs, thus enabling the practical realisation of functional elements. The application frequency range should also be regarded as a positive factor - which typically ranges now from 200 MHz to single GHz.

In the Raman-Nath interaction, several diffraction orders occur simultaneously (Fig. 7). A possible uncertainty in the identification of these orders, results in the fact that the application of this interaction is less popular than that of the Bragg type. Sometimes, it is applied up to frequencies of several hundred MHz.

The collinear interaction is the least popular, since it requires a precise frequency selection of the surface acoustic waves. A slight change of a selected value substantially reduces the interaction efficiency. Therefore, in further considerations, in order to calculate parameters of the planar systems, the two first types of interaction would be taken into account, particularly the Bragg interaction.

While considering the Bragg interaction, a general description of the optical waves [16] may be as follows:

- for the incident wave:

$$\vec{E}_m\,(x, y, z, t) = \frac{1}{2}\, e_m\,(x)\, \vec{E}_m\,(y) \exp \left[j(\omega_m t - \beta_{xm} x - \beta_{zm}) \right] + \text{c.c.} \qquad (4.4)$$

- for the diffracted wave:

$$\vec{E}_n\,(x, y, z, t) = \frac{1}{2}\, e_n\,(x)\, \vec{E}_n\,(y) \exp \left[j(\omega_n t - \beta_{xn} x - \beta_{zn}) \right] + \text{c.c.} \qquad (4.5)$$

where:

m, n – mode numbers;
$e_m(x)$, $e_n(x)$ – wave amplitudes;
$\vec{E}_m(y)$, $\vec{E}_n(y)$ – distribution functions;
β_{xm}, β_{xn}, β_{zm}, β_{zn} – components of the propagation constants;
ω_m, ω_n – wave pulsation;
c.c. – coupled constants.

A surface acoustic wave, propagating in the piezoelectric medium, causes a change in the permittivity of this medium, which is described as follows:

$$\overline{\Delta\varepsilon}\,(x, y, z, t) = \frac{1}{2}\,\Delta\varepsilon\,(y) \exp \left[j(\Omega t - Kz) \right] + \text{c.c.} \qquad (4.6)$$

where:

$\Delta\varepsilon(y)$ – permittivity distribution function;
Ω – acoustic wave pulsation;
K – wave vector for the acoustic wave.

In order to determine the efficiency of the interaction of the acoustic wave with the light wave, defined as the ratio of diffracted wave intensity to the incident wave intensity, the wave equation should be solved first:

$$\left[\frac{\delta^2}{\delta x^2} + \frac{\delta^2}{\delta y^2} - \varepsilon\mu \frac{\delta^2}{\delta t^2} \right] \vec{E}_m = \mu \frac{\delta^2 \vec{P}_n}{\delta t^2} \qquad (4.7)$$

where:

μ – magnetic permeability, and

$$\vec{P}_n(x, y, z, t) = -\varepsilon\, \overline{\Delta\varepsilon}\,(x, y, z, t)\, \vec{E}_n\,(x, y, z, t) \qquad (4.8)$$

is an input forced by the surface acoustic wave.

To solve the equation (4.7) a perturbation method is used. Taking into account that field E_m must satisfy the condition of homogeneous equation (zero–order approximation of the perturbation method) an the condition of slow amplitude change

$$\left[\frac{\delta^2 e_m\,(x)}{\delta x^2} \ll \frac{\delta e_m\,(x)}{\delta x} \right],$$

equation obtain the equation (4.9), which binds the amplitudes of the incident wave $e_m(x)$ and that of the diffracted wave $e_n(x)$:

$$\frac{\delta e_m\,(x)}{\delta x}\, \vec{E}_m(y) = j\, \frac{\mu\varepsilon\, \overline{\Delta\varepsilon}\,(y)}{\beta_m \cos\Theta_m}\, e^{j(\Delta\beta_x + \Delta\beta_z z)}\, x \; x\, \frac{1}{2}\, \omega_n^2 e_n\,(x)\, \vec{E}_n\,(y) \qquad (4.9)$$

where:

$$\Delta\beta_x = \beta_{mx} - \beta_{nx} = \beta_m\cos\Theta_m - \beta_n\cos\Theta_n$$
$$\Delta\beta_z = \beta_{mz} - \beta_{nz} - K$$

Θ_m – angle of the incident wave (equivalent to ψ_2 – Fig. 7b)

Θ_n – angle of the diffracted wave.

The system of coupled equations, describing respectively the amplitude of the incident wave $e_m(x)$ and the amplitude of the diffracted wave $e_n(x)$, may be presented as follows

$$\frac{\delta e_m(x)}{\delta x} = j\,\frac{\omega_n^2}{2c^2\beta_m\cos\Theta_m}\,e_n(x) \qquad (4.10)$$

$$\frac{\int_{-\infty}^{\infty} \vec{E}_m(y)\overline{\Delta\varepsilon}\,(y)\ \vec{E}_n(y)dy}{\int_{-\infty}^{\infty} |E_m|^2\,dy} \times\ \exp\left[j(\Delta\beta_x x + \Delta\beta_z z)\right]$$

$$\frac{\delta e_n(x)}{\delta x} = j\,\frac{\omega_m^2}{2c^2\beta_n\cos\Theta_n}\,e_m(x) \qquad (4.11)$$

$$\frac{\int_{-\infty}^{\infty} \vec{E}_n(y)\overline{\Delta\varepsilon}\,(y)\ \vec{E}_m(y)dy}{\int_{-\infty}^{\infty} |E_n|^2\,dy} \times\ \exp\left[-j(\Delta\beta_x x + \Delta\beta_z z)\right]$$

The system of coupled equations (4.10) and (4.11) should be solved with the boundary conditions, expressing the exclusive existence of the incident wave at the beginning of the interaction area, i.e.:

$$e_m(x)|_{x=0} = e_{m_o}$$

For easier considerations, equations (4.10) and (4.11) are transformed to another form (4.12), exposing the coupling coefficients (Γ_{mn}, Γ_{nm}) for the incident and diffracted wave:

$$\frac{\delta e_m\ (x)}{\delta x} = j\Gamma_{mn}e_n\ (x)e_j^{\,j(\Delta\beta_x x + \Delta\beta_z z)}$$

$$(4.12)$$

$$\frac{\delta e_n\ (x)}{\delta x} = j\Gamma_{nm}e_n\ (x)e_j^{\,-j(\Delta\beta_x x + \Delta\beta_z z)}$$

where:

$$\Gamma_{mn} = \frac{\pi}{\lambda_o\ n_m\cos\Theta_m}\,\frac{\int\vec{E}_m\ \overline{\Delta\varepsilon}\ \vec{E}_n dy}{\int|E_m|^2\ dy},$$

$$\Gamma_{nm} = \frac{\pi}{\lambda_o\ n_n\cos\Theta_n}\,\frac{\int\vec{E}_n\ \overline{\Delta\varepsilon}\ \vec{E}_m dy}{\int|E_n|^2\ dy},$$

λ_o – light wavelength in vacuum.

Coupling coefficients Γ_{mn}, Γ_{nm} are the most important elements in describing the incident and diffracted wave coupling, for the diffraction in the field of interaction of surface acoustic waves. They include in their values the integrals of coverage of the optical fields $\vec{E}_m(y)$, $\vec{E}_n(y)$ and the disturbance field $\overline{\Delta}\varepsilon(y)$. The value of the coupling coefficients depends on the degree of coverage of these fields and on the disturbance level, so does the effectiveness of energy transfer from the incident to the diffracted wave. Solving the equation system (4.12) results in the determination of the amplitude of the diffracted wave $e_n(x)$, thus enabling the determination of the effectiveness of energy transfer, defined as the ratio of the intensity of the diffracted beam to the intensity of the incident beam:

$$\eta = \frac{|e_n\ (L)|^2}{|e_m\ (O)|^2} \qquad (4.13)$$

where L is the perturbation length.

The effectiveness of the Raman-Nath interaction may be determined using the analogy of the description of the spatial and planar acousto-optical elements [17].

Similarly, as in the Bragg interaction, the effectiveness of the Raman-Nath diffraction is determined by the overlapping of the optical and acoustic fields.

Prior to undertaking the experimental research, calculations on the effectiveness of the Raman-Nath and Bragg interactions had been performed. The results of the calculations were compared with the empirical results in the second part of the paper.

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