Optical radar processor:

Part II. Structure and experimental investigations of the optical radar processor

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The structure, manufacturing technology, methods and results of laboratory research of the optical radar processor elaborated according to the original concept, have been presented. The processor have been examined under exposure to optical radiation and then to radio frequency radiation. Also, examinations in the conditions of an acousto-optical interaction for two diffraction modes were performed. The comparison of the experimental result and theoretical calculations have been made.

1. Introduction

In the first part of this paper, the advantages were presented resulting from the optical processing of the radar echo signal and from the application of optical processors in the systems of control of antenna array radar beams and in radioelectronic recognition. The circuits and methods of signal optical processing presented in various references were reviewed. Theoretical considerations are presented which preceded the design and realization of the own multifunction optical processor of the partially integrated structure, which, ensuring two types of diffraction and subassembly exchangeability, could serve as the base for building in the future totally integrated processor for specific applications.

This part of the paper presents the process of development of the optical processor and the methods and results of examinations performed on it. Energetic parameters of the circuit were evaluated, trials for two operation modes were performed - for the Raman-Nath diffraction and for the Bragg diffraction. The results of the experiments were compared with the calculation results. Conclusions and final comments are also included.

2. Elaboration of the processor structure

It was assumed that the processor should ensure the realisation of the Raman-Nath interaction and the Bragg interaction. Therefore, it was necessary to maintain the possibility to change the laser beam incident angle with the reference to the propagation direction of the acoustic wave in modulator (90° in the Raman-Nath interaction and $\psi_2 = 90^\circ - \theta_B$ for the Bragg interaction (Part I – Fig 7). Besides, the possibility of exchanging of the optical transforming circuit and photodetector set was assumed. The assumed conditions determined the structure of the processor (Fig. 1). The laser light modulator was made using the integrated optics technology, the collimator and optical transforming circuit was made applying volume optics technology. Helium-neon laser was a source of the coherent light.

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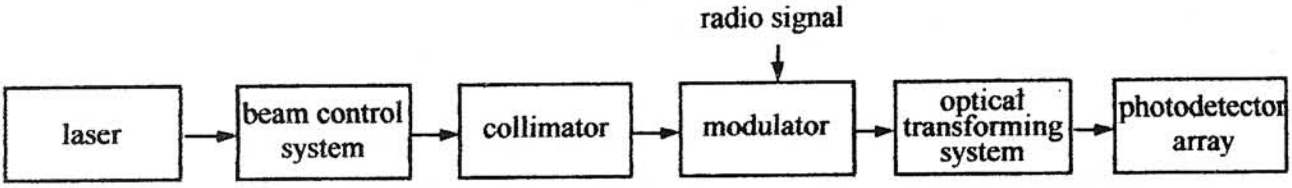

Fig. 1. Processor structure.

The modulator was elaborated on the base of lithium niobate doped with titanium, since this material is characterized with low light attenuation, high electromechanical coupling coefficient and with low attenuation of acoustic waves. Crystals of lithium niobate with the Y cut were used, grown by the Institute of Electronic Materials Technology, Warsaw. Technological processes carried out to make a diffusion waveguide and acoustic transducers of the surface waves were prepared and realized in the Research Center for Technical Physics Applications of the Military University of Technology.

The adopted structure of the processor enables to carry out laboratory research from the point of view of its various applications, though the assumption on cooperation of volume optics elements with the integrated optics system complicated and impeded the research on the processor. The problem consisted in the necessity of introduction of an external laser light, through the prism coupler, into the planar structure and then, to send it out to the optical transforming circuit after the diffraction (Fig. 2).

Preparation of the optical processor of the precisely defined application enables integration of the processor, i.e. placing the whole structure on a common base, i.e.: laser, collimator, modulator, transforming lens and a photodetector array (Fig. 3).

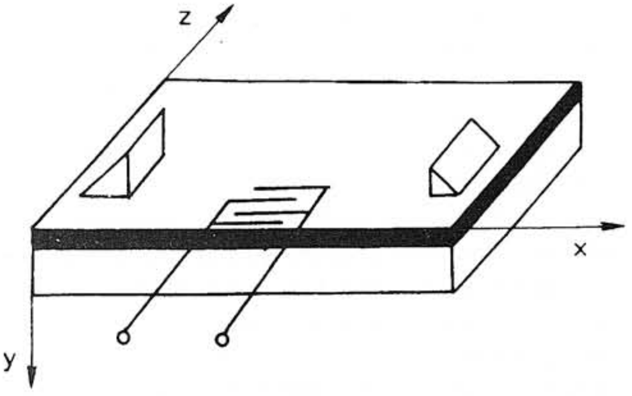

Fig. 2. Integrated laser light modulator.

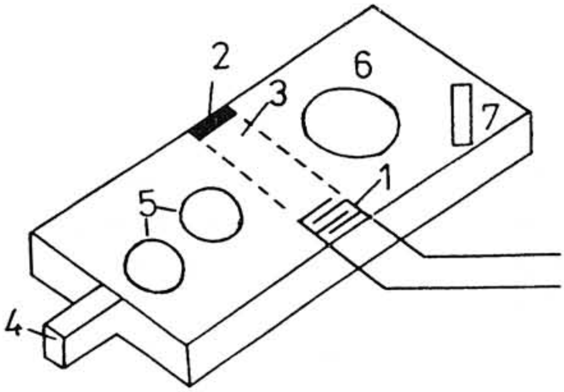

Fig. 3. Integrated processor:
1 – electro-acoustic transducer, 2 – acoustic wave absorber, 3 – acousto-optical interaction space, 4 – laser, 5 – collimator, 6 – transforming lens, 7 – photodetectors array

3. Technology of processor

The most difficult was to elaborate laser light modulator (Fig. 2). It consists of a waveguide made in the LiNbO$_3$ crystal and a set of transducers exciting surface acoustic waves on the waveguide surface.

The introducing of laser beam into the waveguide and leading it out is performed with the use of prisms. The refractive index of the material of the prism must be bigger than the refractiwe index in the waveguide. In order to ensure better coupling, an air gap should exist between the waveguide surface and the prism, the size of which is much smaller than the optical wave length.

Acoustic surface wave is excited with the interdigital transducer, the frequency of which depends on the pin width and the separation between pins.

Prior to be used in the waveguide, the lithium niobate monocrystal was grinded and polished up to the optical smoothness. Particular attention was paid to obtain appropriate flatness and parallelism of the surface of the processed element.

Optical examinations were performed for the two polishing methods; some samples were polished with the use of diamond paste with grain of 0.5 μm in diameter, while the rest were polished mechanically and chemically with a SiO_2 colloid, delivered by the Institute of Electronic Materials Technology, Warsaw. It was observed that the samples polished with the diamond paste have bigger scattering on the surface, caused with the structure defects from diamond grains. The second method gives much better results in this respect, but it deteriorates the surface flatness on crystal edges. So the best solution was to perform the initial polishing with the diamond paste and then to finish with the mechanical – chemical processing.

The next phase was doping with titanium. A titanium layer of thickness 400–600 Å thick was deposited with the cathode sputtering method. Diffusion of titanium into the lithium niobate was performed in the argon ambient at the temperature of approx. 1000° C. Then the sample was cooled down in the oxygen ambient. A ready waveguide was checked with respect to light introducing guiding.

The next steps consisted in creation of a transducer of the acoustic surface waves on the surface of the waveguide. For this purpose, part of the waveguide was coated with an aluminium layer of thickness 2000 Å (by vacuum evaporation), then a light sensitive layer was deposited, heating was performed and a pattern of the interdigital transducer was copied from a photolithographic mask. After development and etching, the transducer was equipped with a contact points for the control signal.

Thus obtained integrated laser light modulator (Figure 2) was examined and then incorporated into the optical processor structure (Figure 1), in which also the following elements were used:

– Helium – neon laser of the output power of 8 mW, operating wavelength of 0.6328 μm.

– Beam control circuit, including a mechanical beam breaker, polarizer and eliminator of transverse modes.

– Collimator, ensuring a parallel light beam of 300 μm in diameter.

– Optical transforming circuit.

– nonaberration lens delivered by the Polish Optical Factory (PZO)

– Set of photocouplers, equipped with photodiodes or phototransistors, depending on the beam intensity.

Below, the methods and results of examination of the modulator as well as of the complete optical processor are presented.

4. Structure of laboratory measurement systems

In order to carry out experiments, the elaborated radar optical processor was connected to high frequency generation line, which produced radio signals for the modulator (Figure 4). To enable selection of the processor operation mode, the modulator was placed on the rotated plate, for which the light incident angle during an acousto-optical interaction could be determined with the accuracy of 2 minutes. The whole system was assembled on the optical bench.

In the high frequency optical line the capability was added to generation signals of the frequency from the range 30–1200 MHz and of the output power up to 1 W. Pulse generator ensured pulse width control within the range 0.1–10 μs and control of the amplitude from 0 to 100 V. Direction coupler using strip lines was used for measurements of the incident and reflected waves, exciting the surface acoustic wave transducer in the modulator.

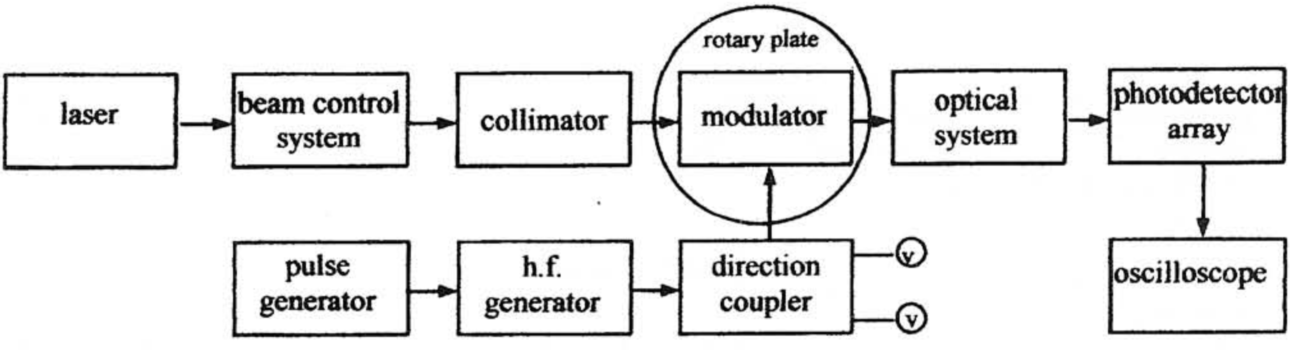

Fig. 4. Optical processor laboratory measurement system.

Examination of surface acoustic waves in the laser light modulator was carried out using the circuit presented in Figure 5, after disconnecting the modulator from the optical processor structure. Two measurement receivers were prepared; of the frequency range 50–400 MHz and 400–1800 MHz, ensuring power measurements within the range 10^{-6}–10^{-12} W, while the range width was 1 MHz.

5. Methods and experiments

5.1. Examining the problem of entering laser light into the modulator

To ensure the operation of the processor in the two diffraction modes, it was necessary to consider the problem of entering laser light into the modulator planar waveguide. The solution was adopted in which the laser beam was coupled with the planar waveguide by means of a prism (Figure 5). Here, the TiO_2 prisms were used featuring the refracting index $n = 2.58$. Some variants of transverse prism cross-sections were examined, since the excitement of the respective mode in the waveguide is obtained through selection of the appropriate light incident angle with respect to the prism. It gives the synchronism of the horizontal components of the wave vector in the prism and in the waveguide layer. During the experiments it was determined that for the case of entering the light with the isosceles prism, a substantial portion of energy is transferred back to the prism. Therefore, the coupling efficiency is very low. Application of the prism of a right-angled triangle cross-section permits to avoid energy loss from the waveguide. However, this solution requires a big force that clamps the prism to the waveguide, which is a construction inconvenience and introduces the risk to damage the junction. Through a series of trials it was determined that equilateral prisms are the most appropriate. Using them, the coupling efficiency of 0.1–10% was achieved, depending on the waveguide and prism quality.

Therefore, for the examined version of the optical processor, equilateral prisms were adopted for a single-mode planar waveguide. The change of the refracting index was $\Delta n = 0.01$, and the diffusion depth $D = 2\ \mu m$ (Part I, Figure 5).

In Fig. 6 the shape of light signal on the output of the modulator was presented for the case when the modulator controlling signal is not present (the case without the large frequency signal).

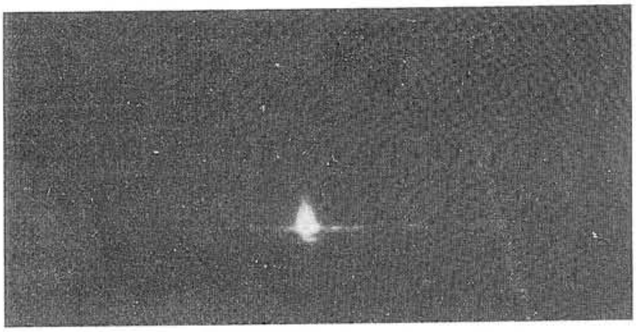

Fig. 6. Light signal in the modulator output, without control signal.

5.2. Attenuation of acoustic surface waves as a function of the radio signal frequency

A dependence of attenuation of acoustic surface waves on radio signal frequency (control signal) was investigated in the circuit shown in Fig. 5. A high frequency generator connected to a modulator was controlled by a rectangular signal, the amplitude of which was 1V and length 0.3 μs. A delayed acoustic signal from the modulator was transforming the output transducer connec-

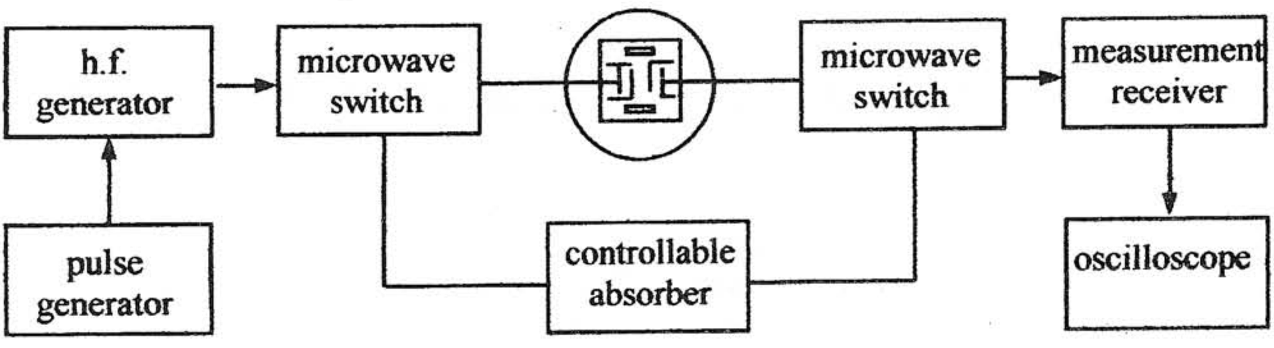

Fig. 5. Laboratory system for modulator examination.

ted to the receiver. The output signal of the receiver, of the particular amplitude, was observed with an oscilloscope. Then, instead of the modulator, a controlled attenuator was used, with which the same amplitude was obtained. Value of attenuation was read from the attenuator and the frequency from the high frequency generator.

In order to determine, whether a generated acoustic wave is the surface wave , its velocity was investigated by determination of the delay of the acoustic pulse on the way between transducers. Loading the surface of the modulator with a thin layer of ether constituted the additional test to determine whether it was a surface wave. The effect of acoustic pulse attenuation, thus obtained, was vanishing with ether vaporization.

The measurement procedure, described above, enabled to select and improve acoustic surface waves transducers, that were prepared earlier.

5.3. Modulation signal power and efficiency of laser beam modulation

Power of the high frequency signal exciting the acoustic transducer of the surface waves can be determined according to the equation:

$$P = \frac{U_p^2 - U_o^2}{Z_o}$$

where:
U_p – effective value of the incident wave voltage,
U_o – effective value of the reflected wave voltage,
Z_o – impedance of the high frequency line.

Values Up and Uo are measured in the high frequency line using the direction coupler (Fig. 4).

Efficiency of the laser light modulation was determined (Fig. 4), observing with an oscilloscope the output signal level of the processor without the high frequency modulation and then, the output signal level after the acousto-optical interaction. The pulse obtained by the measurement of modulator efficiency is shown in Fig. 7. Both signals, mentioned above, are easily distinguishable on the oscilloscope screen, due to the length difference (length ratio 1 : 5). As a result of amplitude reading from the oscilloscope screen, the efficiency of the laser light modulation is obtained. For the presented case it was $\eta = 50\%$.

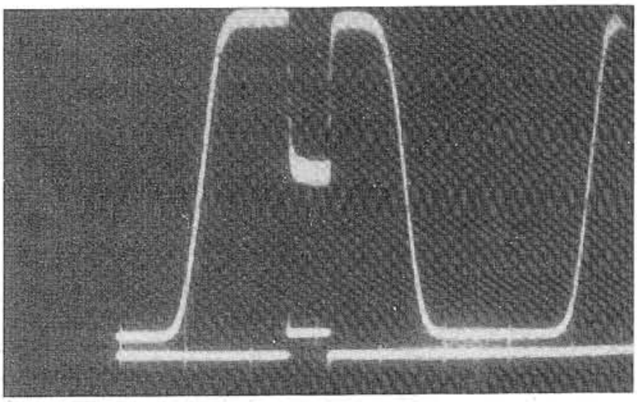

Fig. 7. Measurement of the effectiveness of the laser light modulation.

5.4. Examination of the processor in selected diffraction modes

To ensure operation of the optical processor in the Raman-Nath mode, the angle between the input light beam and the acoustic wave propagation direction was set as $\psi_1 = 90°$ (Part I, Fig. 7). An acoustic surface wave was excited on the planar waveguide surface with the use of interdigital transducer of the basic frequency of 73 MHz. The aperture length of the transducer was 4 mm and the number of electrodes was 25.

In the frequency range of 40–90 MHz, an effect of the Raman-Nath diffraction was observed, presented in Fig. 8. A change in control signal frequency caused a change in the diffraction angle. The measurements of the diffraction angles for the three diffraction orders are presented in

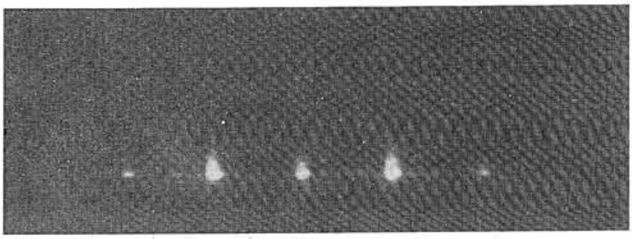

Fig. 8. Light signal in the modulator output for the Roman-Nath operation mode.

Fig. 9. While examining the diffraction efficiency, the highest value was obtained for the control signal frequency of 72 MHz. For this frequency the results of measurements and the results of efficiency calculations as a function of the control signal power, were presented in Fig. 10.

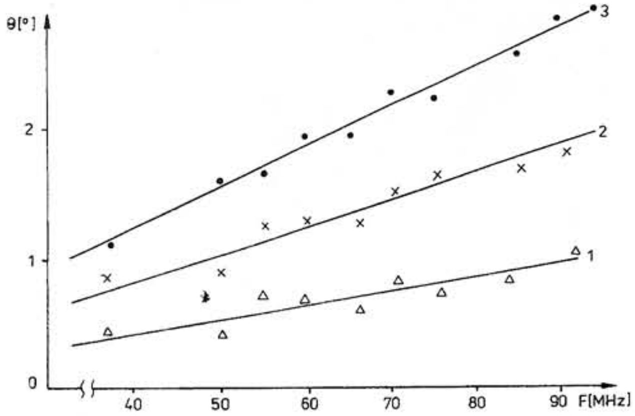

Fig. 9. Light deflection angles as a function of control signal frequency, for the first three diffraction orders.

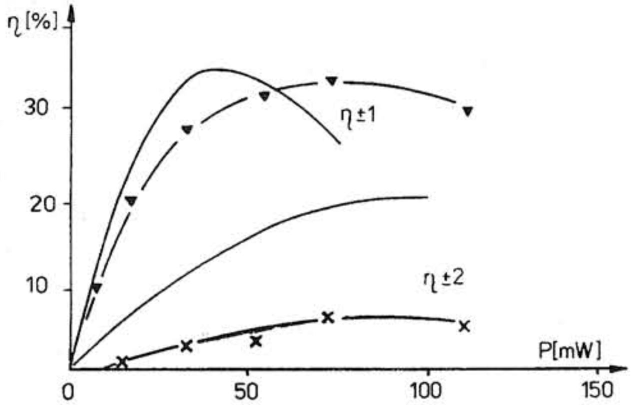

Fig. 10. Diffraction efficiency as a function of control signal power.

Operation of the processor in the Bragg mode was ensured with setting the angle ψ_2 (Part I, Fig. 7) between the input light beam and the acoustic wave propagation direction. The value of this angle is the right angle subtracted with the Bragg angle. The processor was operating near the third harmonic frequency (215−225 MHz), the basic frequency of acoustic surface wave transducer. For the control signals of the power of several hundred milliwatts the diffraction efficiency of the order of 50% was achieved.

In order to increase the Bragg diffraction efficiency, the next modulator was prepared with the acoustic surface wave transducer of the basic frequency of 140 MHz. After the modulator in the processor was exchanged, a very high diffraction efficiency was achieved and a high coincidence of the experimental and calculation results was obtained (Fig. 11).

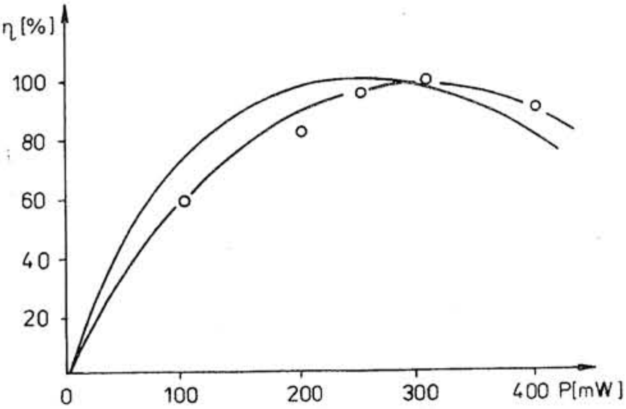

Fig. 11. Diffraction efficiency as a function of control signal power.

6. Final conclusions and remarks

The optical processor, discussed above, was developed with the assumption of elements exchangeability. This constituted a technological obstacle, but such solution enables to change operation conditions of the processor by exchanging the modulator, optical transforming circuit or photodetector set. Due to the present capabilities of domestic photolithography, the processor is operating at relatively small frequencies of radio signals (control signals). According to the variant of the laser light modulator, basic frequencies of acoustic surface wave transducers are 73 MHz or 140 MHz.

Thus, the microwave radar processor operation is possible, while the conversion circuit is applied. However, introducing conversion circuit prior to radar signal optical processing structures may be regarded as a rule adopted by the renowned world companies.

The experience acquired while developing and examining the presented processor may be used when elaborating its application variants. The elaborated processor model, due to exchangeability of its elements, allows optimization of the final solutions according to a purpose. When elaborating utilizable versions, one should aim at obtaining fully integrated processor (Fig. 3). It will assure high reliability and small dimensions. Problems with entering laser light into the modulator through a prism will be solved. The necessity to ensure a change in the angle between the light propagation direction and the acoustic wave propagation direction will be eliminated. Also, the laser light control unit will be simplified substantially.

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