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Spatiotemporal Search for Pulsed Radiation in the Photon Flux Detection Mode with Prolonged Observation Time of the Decomposition Element

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Abstract. The development of science and technologies of microwave frequencies (UHF) has contributed to the fact that the use of ultra-wideband (UWB) pulsed signals has emerged as a separate scientific and technical area of radiophysics, requiring a deeper study of the methods of formation, emission, reception and processing of such signals. Aperture radiators are mainly used to transmit UWB signals. This type of emitters is a variety of modifications of mirror antennas, horn antennas of various shapes and profiles, open waveguides, planar and conformal antenna arrays, as well as lens antennas. The classical theory of analysis of radiation and propagation of electromagnetic signals is well known, but its application to the synthesis of UWB emitters in the time domain often becomes too cumbersome and incorrect. Progress in the fields of radar, communications, and radio astronomy in the 1960s stimulated the creation of aperture theory based on physical optics approaches. This theory makes it possible to analyze and calculate the characteristics of mirror radiators and antenna arrays with sufficient accuracy for practical application. It is often possible to use the aperture theory to analyze some horn emitters that have a large radiation surface relative to the spatial dimensions of pulsed signals.

1 Introduction

In 1989, for the first time, a method was proposed for synthesizing the impulse response (IR) of an arbitrary aperture in the near field, based on the aperture theory. The IR calculation method made it possible to calculate the time responses of the EM field at any point in front of the emitter by means of a mathematical operation of convolution of the pulse signal that excites the aperture with its analytical IR [1]. Over the next two decades, the scope of the IR calculation method for the analysis of EM fields has expanded significantly. Abroad, this method has been studied and applied in various fields of radiophysics. Here we can note the works of Karl Baum, who used the proposed theoretical approach to analyze the field of a pulsed signal, and a group of French scientists (R. Olivier

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and M. Elie), who applied the method of calculating the IR to study parabolic radiators. A significant proportion of the articles was devoted to the very method of analyzing EM fields and how to use it. In such publications, the authors mainly researched and developed new types of radiators with different aperture shapes, and also carried out a scientific search for new methods for measuring antenna characteristics in the near field with small and large probe antennas without using an anechoic chamber. The criteria of the far zone, restrictions on the minimum size of the aperture during the emission of a UWB signal were investigated [2]. Somewhat later, papers were published in which the concept of illumination of a circular aperture or the distribution of instantaneous values of the EM field strength was introduced and IRs were obtained in the near and far zones for various distributions. The IR calculation method is analytical, therefore, its results allow one to obtain a physical interpretation of the processes of radiation and propagation of UWB pulse signals. When calculating specific emitters, it is necessary to refine the method and determine the applicability criterion, which is especially important in the development of new UWB radar and radio communication systems. Thus, the development of methods for analyzing the EM fields of aperture emitters operating with UWB nano- and subnanosecond pulse signals seems to be relevant and requires further research.

2 Research Methodology

In the works noted above, it was considered that the criterion that determines the possibility of using the IR calculation method for analyzing EM fields of aperture emitters is the ratio narrow region of space can be rewritten as: $D \gg \tau c$ (where τ is the pulse duration) [3]. However, this criterion is not quite certain in relation to the accuracy of the method for calculating the IC with boundary ratios. It is also noted that the factor that determines the contribution of the elementary aperture emitter to the EM field of the observation point (hereinafter referred to as the polarization factor) was used only for vertical or horizontal deviation from the central axis. The distribution of instantaneous values of the field strength over the aperture during the emission of a pulsed signal was considered only for round apertures, and was considered constant for rectangular and arbitrary apertures. The application of the IR calculation method to study more complex structures and radio systems, in contrast to a flat aperture, is not fully covered in the literature and mainly concerns the analysis of round flat apertures of mirror parabolic antennas.

When solving the tasks set, methods of aperture theory, physical optics and diffraction theory, methods of mathematical and numerical modeling of electrodynamic systems were used. When constructing analytical models of aperture emitters and deriving the polarization factor, methods of mathematical analysis, experimental methods of radiophysics and the theory of electrical circuits were used. Electrodynamic modeling was carried out using the numerical method of finite integrals for solving the system of Maxwell equations. Signal processing was carried out in the Matlab mathematical package.

3 Results and Discussions

To test the analytical method for calculating IR, the thesis developed a numerical model of a flat circular aperture emitting a plane linearly polarized wave along the Y axis (Fig. 1). Perfectly matched absorbing layers were set at the boundaries of the computational region in order to prevent re-reflections [4]. The radius of a round metal plate is R = 0.5 m. In this work, modeling was carried out by the method of finite integrals in the time domain (FIM). As a result, instantaneous field distributions in front of the aperture and temporal realizations of the electric field at points on the probes were calculated. It was found that the field radiated by a circular aperture consists of: the main wave - 1, coinciding in shape with the aperture, and the boundary toroidal wave - 2, associated with re-reflection from the boundaries and edge effects (Fig. 2) [5]. With the use of numerical results, a circular aperture IR was extracted from the obtained field responses on the probes and the exciting UWB signal for comparison with the analytical IR. Regularization was used according to the method of A. N. Tikhonov when calculating the ratio of the spectra. The IRs calculated in this way qualitatively coincided with the analytical ones, however, a quantitative comparison was not possible due to regularization errors, which underestimate the contribution of small spectral components.

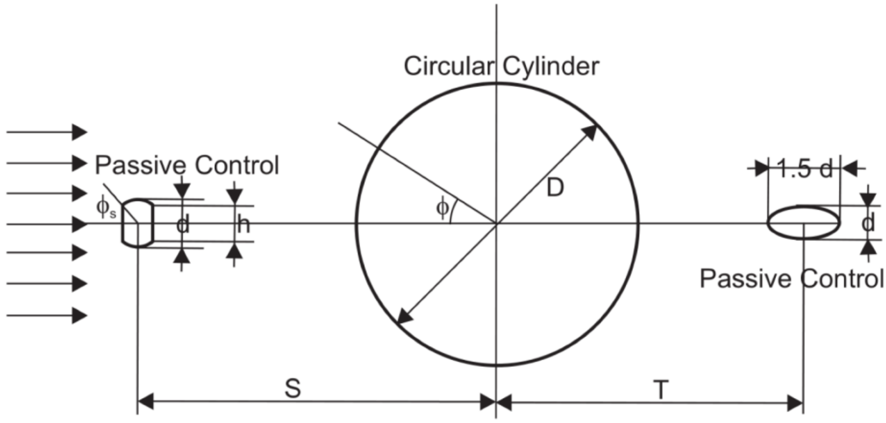

Fig. 1. Scheme of the round model apertures for numerical analysis

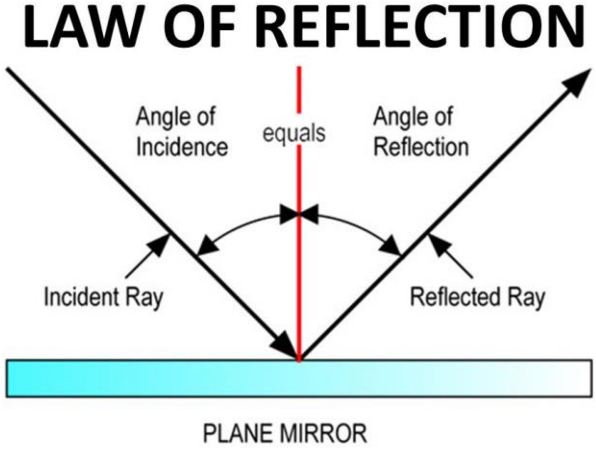

Fig. 2. Reflection of a plane wave from round plate

It is shown that the analytical space-time method for calculating the impulse responses for aperture emitters allows one to obtain primitive IR, and then, using the mathematical operation of convolution with a signal in the aperture, calculate the time dependence of the EM field at any point in front of the emitter. As a result of the comparison of the accuracy of calculating the responses of the EM field by analytical and numerical methods at different distances from the aperture plane and from the axis of the aperture, a criterion for the applicability of the theory of the IC calculation method is proposed [6]. An estimate of the time computational complexity of the analytical (calculation of IR) and numerical (finite integrals in the time domain) methods is presented, on the basis of which a conclusion is drawn about the advantages in the speed of the first.

Let the search equipment register a photoelectron (or ITT) at the moment when the spatial element of decomposition is surveyed. In this case, the equipment becomes insensitive to the reception of PE and ITT in the interval . Here corresponds to the moment of the beginning of the action of the strobe pulse during the re-examination. The delay time between the moment of operation of the HELL and the moment of generation of the 1st photoelectron (or ITT) is equal to . The re-interrogation is carried out in the interval . Here corresponds to the end of the action of the strobe pulse during the re-examination.

If the discrimination level is not exceeded during the reanalysis, the equipment continues the examination of the time interval [7].

Let in the process of continuing the examination of the spatial element of decomposition, the operation of the IM is again recorded. The equipment goes into standby mode. The re-interrogation is performed during the action of the second strobe pulse. If the AD is triggered, then a decision is made to receive the signal. Otherwise, a decision is made to terminate the examination of the spatial decomposition element.

False alarm probability. The Poisson distribution is used to describe the statistical properties of the photon (photoelectron) flux.

It can be seen from formula (20) that, in order to reduce the probability of false alarms, it is necessary to generate optical pulses of nanosecond and picosecond duration, imposing strict requirements on the stability of the repetition rate of the latter.

The probability of false alarms depends on the duration and repetition period of a rectangular optical pulse, the instability of the optical pulse repetition period, the parameters of a single-photon photoemission device (the number of dynodes, the bandwidth of the OFEC), the threshold level of amplitude discrimination, and the frequency of generation of noise pulses [8].

As expected, with an increase in the average number of noise pulses generated during the repetition period of optical pulses, the probability of false alarms increases [9]. A tenfold decrease in the frequency of appearance of noise pulses makes it possible to reduce the probability of false alarms by a factor of 100 and, as a result, to reduce the average time of spatiotemporal search for pulsed signals in the single-photon pulse registration mode.

The analysis shows that the price for the admissibility of two false positives in the equipment when reviewing the spatial decomposition element is an increase in the probability of a false alarm. This is equivalent to the requirement that the transmitter of the search complex generate light pulses of shorter duration. However, the difference in RLT values is not large.

The analysis of the polarization factors used in the literature, intended for the analysis of the electromagnetic field of the aperture emitter inside the searchlight beam, is carried out. An explicit form of the polarization factor is obtained by searching for the radius of the section of the radiation pattern of an elementary aperture emitter [10]. The revealed factor increases the convergence of the analytical and numerical methods by 1.5 times when estimating the temporal realization of the main wave field and by 5 times when estimating the maximum value of the main wave strength. 3. A method is presented for minimizing the phase difference of the wave front in the aperture of the UWB TEM-horn emitter by filling the opening space with an inhomogeneous dielectric material (lens) [11]. Numerical simulation has been performed to test the phase difference compensation method and the distribution of instantaneous values of the field strength in the emitter aperture has been determined. It has been established that the distributions of strengths and phases in the aperture for the experimental sample and the model of the TEM horn coincide. For the first time, an analytical form of the distribution of instantaneous values of the field strength in a rectangular aperture was proposed and a high degree of agreement with the numerical model was found [12]. The paper shows that the method of calculating the impulse response can be used to analyze the electromagnetic field inside the searchlight beam of a rectangular aperture emitter when the relationship between the spatial size of the pulse signal and the aperture proposed in the paper is fulfilled.

4 Conclusions

Numerical modeling of the UWB communication channel by the finite integral method was performed, as a result of which the signal at the output of the receiving antenna was calculated for various distances between the apertures, and a method was proposed for taking into account the distortion of the input pulse when passing through the radiator structure, which made it possible to relate the aperture excitation signal and the voltage at the radiator input. Using the method of calculating the impulse responses, an analytical model of the communication channel is proposed, which makes it possible to calculate the signal at the output of the receiving antenna from a given UWB pulse signal at the input of the transmitting aperture radiator. An experimental setup has been developed for measuring the output signals of a UWB communication channel at various distances between the apertures of TEM horns, which were used as an emitter and receiver. As a result of the experimental work, the measured output signals coincide with both the theoretical ones, calculated by the impulse response method, and those obtained in numerical simulation. Based on the completed study, a conclusion is made about the possibility of using the proposed model to describe the UWB communication channel using the analytical method for calculating impulse responses. Following the basic principles of the scientific method of research, the dissertation contains the necessary elements: theory, computer simulation, experiments. Each element of the scientific approach was subjected to analysis and justification, and also appears to be a complete, independent unit. This indicates a complete and complete scientific research.

References

1. S. I. Bychkov, K. E. Rumyantsev, Search and detection of optical signals: Monograph, 282 (2000).
2. K. E. Rumyantsev, Registration of the fact of receiving a multiphoton pulse in a quantum key distribution system based on a single-photon photomultiplier, **11**, 67-69 (2011).
3. K. E. Rumyantsev, A. E. Ampliev, Requirements for a binary counter for registering a photon flux. Izvestiya vuzov Rossii. Radioelectronics, **5**, 79-91 (2011).
4. K. E. Rumyantsev, A. N. Sukovaty, Selection methods for single-electron noise pulses: a review, **6**, 56-61 (2004).
5. K. E. Rumyantsev, I. E. Khairov, Registration of optical radiation in search systems of astronavigation and astroorientation with time selection of single-electron pulses, **8**, 45-49 (2004).
6. K. E. Rumyantsev, I. E. Khairov, Information protection in photonic telecommunication systems - a new technology for data transmission, **4**, 329-330 (2003).
7. K. E. Rumyantsev, M. Kh. Omar, I. E. Khairov, Operating characteristics of optimal receivers of optical radiation, **10**, 39-44 (2003)

8. K. E. Rumyantsev, L. A. Albogachieva, K. B. Bamatgireeva, Algorithm for spatio-temporal search for pulsed signals in the single-channel registration mode of single-photon pulses, **8(4)**, 3-11 (2012).
9. K. E. Rumyantsev, K. B. Bamatgireeva, Probabilistic characteristics of the algorithm for spatio-temporal search for pulsed radiation with single-channel information processing, **3(20)**, 70-77 (2014).
10. L. A. Albogachieva, K. E. Rumyantsev, Temporal characteristics of the algorithm for a single-channel space-time search for pulsed radiation, **3(20)**, 62-69 (2014).
11. K. E. Rumyantsev, K. B. Bamatgireeva, Probabilistic characteristics of the algorithm for spatio-temporal search for pulsed radiation with single-channel information processing, **3(20)**, 70-77 (2014).
12. K. E. Rumyantsev, L. A. Albogachieva, K. B. Bamatgireeva, Algorithm for spatio-temporal search for pulsed signals in the single-channel registration mode of single-photon pulses, **8(4)**, 3-11 (2012).