REPUBLIC OF AZERBAIJAN

On the rights of the manuscript

ABSTRACT

of the dissertation for the degree of Doctor of Science

THE ANALYSIS AND OPTIMAL SYNTHESIS OF THE COMPLICATED-STRUCTURAL MICROWAVE WAVEGUIDE SYSTEMS IN THE NON-LINEAR ENVIRONMENT

Speciality: 3325.01-“ Telecommunication technology”

Field of science: Technics

Applicant: **Islam Jamal oglu Islamov**

Baku-2021

The work was performed at the "Radioengineering and telecommunications" department of Azerbaijan Technical University.

Scientific consultant:	doctor of technical sciences, professor **Elshad Gulam oglu Ismibayli**
Official opponents:	doctor of technical sciences, professor **Isa Rahman oglu Mammadov**
	doctor of technical sciences, professor **Khagani Imran oglu Abdullayev**
	doctor of technical sciences, professor **Bayram Ganimat oglu Ibrahimov**
	doctor of technical sciences, professor **Ramin Rza oglu Rzayev**

Dissertation council ED 2.41 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Azerbaijan Technical University.

Chairman of the Dissertation council:
doctor of technical sciences,
professor **Vagif Alijavad oglu Gasimov**

Scientific secretary of the
Dissertation council: candidate of
technical sciences, associate professor **Vahid Gara oglu Farhadov**

Chairman of the scientific seminar:
doctor of technical sciences,
professor **Bayram Ganimat oglu Ibrahimov**

GENERAL CHARACTERISTICS OF THE WORK

The urgency and status of the problem. As the fundamental limit of telecommunication and radioengineering systems is the adoption of increasingly high frequency bands, the exchange of information is increasing day by day in the XXI century, which is the century of information and communication. It is known that waveguide systems are widely used in the lossless transmission and reception of information in the microwave range, which has a wider information capacity and speed. The microwave bandwidth systems used to transmit information are of various constructions and purposes and are used in telecommunications, television, radar, radio navigation, medical technology, radio control, communication technology, antenna technology, science and other fields of technology. The most widely used of these waveguides are rectangular and circular waveguides. Microwave rectangular and circular waveguides have a number of advantages. Thus, they have high reliability, stability of parameters and longevity in the process of operation. At the same time, since rectangular and circular waveguides are completely isolated from the environment, the transmission of electromagnetic waves (radiowaves) to the external environment is almost non-linear when transmitting information through such systems.

Despite the widespread use of rectangular and circular waveguides, there are not enough scientific studies that fully reflect the electromagnetic processes propagating in such transmission systems and are of practical importance. A.N.Bogolyubov, V.A.Donchenko, G.F.Zargano, G.P.Sinyavskiy, K.V.Vdovenko, V.V.Krivopustenko, V.A.Katrich, M.V.Nesterenko, E.I.Mikhaylova, S.C.Chen, V.C.Chyu, L.Gong, K.Zang, T.Grik, L.Nickelson, S.Asmontas, A.Zagdani, O.S.Zaxarchenko, S.Y.Martynyuk, P.Y.Stepanenko, in their current work in this field, the medium in which electromagnetic waves (radiowaves) propagate is considered as a linear environment. However, our research has shown that in real practice, in the process of using rectangular and circular waveguides, the environment behaves as a non-linear environment. At the same time, in the works of the above-named scientists, complex classical mathematical devices were used in the modeling of such waveguides, which also increased the error of calculations and made them difficult to perform. Therefore, given the nonlinearity of the environment, there is a serious need to develop new mathematical models and algorithms based on numerical methods to reflect the specific characteristics of rectangular and circular waveguides in order to improve the electrical, magnetic, technical, design and operational parameters and characteristics. The issue is of **great scientific and practical importance**.

On the other hand, in the works of such scientists as L.I.Babak, V.A.Vyushkov, S.Y.Bankov, A.A.Kurshin, V.D.Razevig, M.P. Batura, A.A.Kurayev, C.J.Railton, D.L.Paul, A. Munir, during the optimization of rectangular and circular waveguides with microwave range stepwise synthesis process was used, which was accompanied by the following negative cases:

- significant errors occurred in the geometric dimensions of the devices;
- economic and scientific-technical efficiency has decreased due to the impossibility of using optimal information on the results of experimental research and development of facilities.

Therefore, there is a need to solve the problem of multi-criteria optimal synthesis of rectangular and circular waveguides with high reliability, parameter stability and longevity in the process of operation. Thus, the solution of the problem of multi-criteria optimal synthesis of rectangular and circular waveguides with microwave range, improvement of electrical, magnetic, technical, design and operational parameters and characteristics of these devices, synthesis and development of new models with optimal parameters remains an **actual scientific and technical issue**.

Summarizing the above, it can be said that due to the widespread use of microwave rectangular and circular waveguides in production, new waveguide systems with more optimal design dimensions have been developed to improve the electrical, magnetic, technical, design and operational parameters and characteristics of these devices and considering the nonlinearity of the environment, the design is important and **actual** both from a scientific point of view and from a production point of view.

The main purpose of the dissertation. The purpose of the dissertation is to improve the electrical, magnetic, technical, design and operational parameters and characteristics of complex structured microwave rectangular and circular waveguide telecommunication and radioengineering systems in a non-linear environment, synthesis and development of new waveguide models with optimal parameters.

Object of research. The object of research in the dissertation is a complex structure of microwave rectangular and circular wave type telecommunication and radioengineering systems.

The main issues of the research. In order to achieve the set goal, the following issues should be addressed in the case:

- development and application of new mathematical models of electromagnetic field of rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and circular waveguide operating in the frequency range of 9 *GHz* from microwave telecommunication and radioengineering, taking into account the nonlinearity of the environment, types of waves;

- development and application of new mathematical models of electromagnetic field in the coordinate system of a rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and a circular waveguide operating in the frequency of 9 *GHz* from microwave telecommunication and radioengineering, taking into account the nonlinearity of the environment, wave types;

- development of effective algorithms for solving new mathematical models of electromagnetic field of rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and circular waveguide operating at 9 *GHz* frequency, taking into account the nonlinearity of the environment, types of waves;

- improvement of methods of finite elements and finite differences for modeling of electromagnetic fields of *E*-type (*TH*) and *H*-type (*TE*) waves of rectangular and circular waveguides, taking into account the constructive dimensions of these devices, development and application;

- development and analysis of 3*D* models of distribution of electromagnetic field intensities in the elementary regions of a rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and a circular waveguide operating in the frequency range 9 *GHz* for *E*-type and *H*-type waves;

- to study the dispersion compositions of different types of electromagnetic waves propagating in rectangular and circular waveguides from microwave telecommunication and radioengineering devices and to show the effect of field intensities on the dispersion dependencies;

- development of measurement schemes for experimental determination of the intensity of the electromagnetic field of a rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and a circular waveguide operating at a frequency of 9 *GHz*, as well as other parameters of the microwave path;

- development and application of new algorithms for optimal synthesis of *E*-type and *H*-type waveguide microwave band devices;

- development of an algorithm for the process of experimental computational synthesis of rectangular and circular waveguides with microwave range;

- parametric and structural optimization of microwave rectangular and circular waveguides using HFSS and Empipe 3*D* software complex;

- carrying out and application of parametric and structural optimization process using microwave rectangular and circular waveguides HFSS and Empipe 3*D* software complex;

- application of the obtained theoretical and practical results in production and educational process.

The main issues raised in the defense. The main issues raised in the defense are:

1. New mathematical models of the electromagnetic field of a rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and a circular waveguide operating at a frequency of 9 *GHz* from microwave telecommunications and radioengineering, taking into account the nonlinearity of the environment, the types of waves.

2. Non-linear environment, new mathematical models in the coordinate system of the electromagnetic field of a rectangular waveguide operating in the frequency range 4,9-7,05 *GHz* and a circular waveguide operating at a frequency of 9 *GHz* from microwave telecommunications and radioengineering, taking into account the types of waves.

3. Effective algorithms for solving new mathematical models of electromagnetic field of rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and circular waveguide operating at 9 *GHz* frequency, taking into account the nonlinearity of the environment, the types of waves.

4. Improvement of finite elements and finite difference methods for modeling electromagnetic fields of *E*-type (*TH*) and *H*-type (*TE*) waves of microwave rectangular and circular waveguides, taking into account the constructive dimensions of these devices methodology.

5. 3*D* models of distribution of electromagnetic field intensities in the elementary regions of a rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and a circular waveguide operating in the frequency range 9 *GHz* for *E*-type and *H*-type waves.

6. Dispersion composition of different types of electromagnetic waves propagating in rectangular and circular waveguides from microwave telecommunication and radioengineering devices and the effect of field intensities on the dispersion dependencies.

7. Measurement schemes for experimental determination of the electromagnetic field intensity of a rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and a circular waveguide operating at a frequency of 9 *GHz*, as well as other parameters of the microwave path.

8. New algorithms and optimization criteria for optimal synthesis of *E*-type and *H*-type waveguide microwave band devices.

9. Algorithm of the process of experimental computational synthesis of rectangular and circular waveguides with microwave range.

10. The process of parametric and structural optimization of microwave rectangular and circular waveguides using HFSS and Empipe 3*D* software.

11. Methodology for minimizing the maximum function for rectangular and circular waveguides with microwave range.

12. Frequency characteristics of rectangular and circular waveguides with optimized microwave range.

13. A new waveguide system that connects the transmitter and antenna to improve the quality of broadcasting in television towers based on the developed waveguides.

14. Application of theoretical and practical results in production and teaching process.

Scientific novelty of the results obtained in the dissertation. The scientific innovations obtained in the dissertation allow to improve the electrical, magnetic, technical, design and operational parameters and characteristics of rectangular and circular waveguides, and mainly consist of the following:

1. New Cartesian, cylindrical and moving coordinate systems of rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and circular waveguide operating in the frequency range of 9 *GHz* from microwave telecommunication and radioengineering, taking into account the nonlinearity of the environment, types of waves.

2. Effective algorithms for solving new mathematical models of electromagnetic field of rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and circular waveguide operating in the frequency of 9 *GHz* from microwave telecommunication and radioengineering devices, taking into account the nonlinearity of the environment, wave types. This allowed to improve the electrical, magnetic, structural and operational parameters and characteristics of rectangular and circular waveguides by 30-40%.

3. The methods of finite elements and finite differences for modeling the electromagnetic fields of *E*-type (*TH*) and *H*-type (*TE*) waves, taking into account the design dimensions of rectangular and circular waveguides, have been improved, resulting in a frequency of 4,9-7,05 *GHz*. The method of minimizing the extinction coefficient of electromagnetic waves in the range and frequency of 9 *GHz* was developed to a minimum of 2 times.

4. For *E*-type and *H*-type waves, 3*D* models of electromagnetic field strength distribution in the elementary regions of a rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and a circular waveguide operating in the frequency of 9 *GHz* were developed. This allowed us to show how the polarization rates of electric and magnetic fields change in these devices.

5. The dispersion compositions of H_{10} and H_{11} modular electromagnetic waves propagating in rectangular and circular waveguides from microwave telecommunication and radioengineering devices were studied and the effect of field intensities on the dispersion dependencies was shown.

6. Experimental schemes have been developed for the experimental determination of the electromagnetic field intensity of a rectangular waveguide operating in the non-linear medium frequency range of 4,9-7,05 *GHz* and a circular waveguide operating at a frequency of 9 *GHz*, as well as other parameters of the microwave pathway. Theoretically determined parameters and characteristics were experimentally confirmed and it was determined that the relative error in the specified frequency ranges is up to 4% for field intensities and up to 1% for other parameters of the microwave tract.

7. New algorithms for optimal synthesis of rectangular and circular waveguides from *E*-type and *H*-type wave microwave telecommunication and radioengineering were developed and optimization criteria were selected, their advantages were substantiated and based on these algorithms new rectangular and circular waveguides, including .

8. For the first time, HFSS and Empipe 3*D* software packages were used for parametric and structural optimization of microwave rectangular and circular waveguides, and as a result, the design dimensions of telecommunications and radioengineering were improved by 5% and dispersion characteristics by 30-40%.

9. On the basis of the developed waveguides, a new waveguide system connecting the transmitter and the antenna has been developed to improve the quality of broadcasting in television towers.

Research methods. The following research methods were used in the dissertation: finite element method, finite difference method, Lorentz transformation, error theory, differential equation theory, electromagnetic field theory, computer modeling method, Ritz method, Galerkin method, HFSS, Empipe 3*D*, Femlab, Matlab, above relaxation method (Yang method), collocation method and variable separation method.

Degree of accuracy of results. The theoretical results obtained in the dissertation were proved by experiments, confirmed by applications in production and teaching process, and relevant acts were obtained**.**

Practical significance of the dissertation and the degree of justification of the recommendations. New mathematical models for the first electromagnetic field of rectangular and circular waveguides from microwave telecommunications and radioengineering, taking into account the nonlinearity of the operating medium, the types of propagating waves, and the algorithms developed to solve these models in other frequency bands, including optical range can also be successfully applied in the analysis, synthesis and design process.

Personal contribution of the author. The scientific issues raised in the dissertation and the main results obtained were obtained independently by the author. New mathematical models for the electromagnetic field of rectangular and circular waveguides from microwave telecommunication and radioengineering, taking into account the nonlinearity of the environment, the types of waves and the algorithms developed for the solution of these models, developed microwave tracts, the algorithms developed for the optimal synthesis of microwave rectangular and circular waveguides were performed by the author independently or with his participation as a responsible executor.

Implementation and application of work results. The results of the dissertation work were applied in radio relay communication lines in the Television Broadcasting and Satellite Communications Production Union of the Ministry of Transport, Communications and High Technologies of the Republic of Azerbaijan. The annual economic benefit obtained from the application of the results of the dissertation is 116842 AZN. At the same time, the results of the dissertation are applied in the implementation of state-funded research work and teaching process at the Azerbaijan Technical University. The use of the results of the dissertation is approved by the relevant application acts.

Approbation of the dissertation. The main provisions of the dissertation were discussed and appreciated in detail at the following conferences and symposiums: 45th and 46th scientific-technical conference of the teaching staff of AzTU, Baku, 2000, 2001; Republican scientific-technical conference dedicated to the 50th anniversary of AzTU, Baku, 2001; International scientific-technical conference “Communication and science”, Baku, 2002; International scientific-technical conference on “Electronics and informatics-2002”, Moscow, 2002; International scientific-technical conference on “Microelectronic converters and devices based on them”, Baku-Sumgait, 2003; Scientific conference on “Modern problems of informatization, cybernetics and information technologies”, Baku, 2003; International scientific conference dedicated to the establishment of the Istok Research Institute of the Federal State Unitary Enterprise, Moscow, 2003; 4th International scientific and technical conference on “Materials of modern information and electronic equipment-2003”, Odessa, 2003; 4th International conference on “Antenna theory and technology”, Sevastopol, 2003; 6th International conference and exhibition on “Digital signal processing and its application”, Moscow, 2004; 7th International scientific and technical conference on “Improving the efficiency of information processing tools on the basis of mathematical modeling”, Tambov, 2004; Scientific-technical conference of the teaching staff of AzTU, Baku, 2004; International conference on “Information and electronic technologies in remote sensing”, dedicated to the 70th anniversary of academician A.Sh. Mehdiyev, Baku, 2004; International scientific-practical conference dedicated to postal services, Sumgait, 2005; Scientific-technical conference of the faculty of AzTU, Baku, 2005; International scientific-technical conference on “Microelectronic converters and devices based on them”, Taganrog, 2005; International conference on education and technology, organized by the international union for science and technology for development, Calgary, 2005; International scientific-practical conference, Lankaran, 2006; 53rd scientific-technical conference of AzTU faculty and graduate students, Baku, 2007; International scientific-technical conference on “Modern problems of radio engineering, television and communication”, Baku, 2007; International conference on “Application of computer technologies in science and education”, Baku, 2007; 13th International exhibition and conference “Telecommunications and information technologies”, Baku, 2007; International scientific-technical conference “Prospects for the development of modern ICT”, Baku, 2011; International scientific-technical conference on “Modern trends in the development of communication networks: theory and practice”, Baku, 2012; Republican scientific-practical conference on “Modern problems of automation and control”, Baku, 2012; International scientific-technical conference on “Current state and development prospects of ICT”, Baku, 2014; International conference on “Current state and development prospects of ICT”, Baku, 2016; International conference on “Intellectual technologies in mechanical engineering”, Baku, 2016; International symposium on mechanical and mechanical sciences, Baku, 2017; International conference on “Modern communication means” held by the Belarus State Academy of Communications, Minsk, 2017, 2018, 2021; Republican scientific-technical conference on “Establishment of education-research-production mechanism”, Baku, 2018; International conference on “Actual problems of energy supply”, Kiev, 2018; International conference on “Actual problems of mathematics and mechanics”, Baku, 2018; International Conference on “Technology, Culture and International Stability” held by the International Federation of Automatic Control, Baku, 2018; International conference on “Actual problems of energy supply” held by Kiev Polytechnic Institute named after I. Sikorsky, National Technical University of Ukraine, Kiev, 2019; International conference on “Innovative technologies in telecommunications”, Baku, 2019; 1st International conference on “Universities of Azerbaijan and Turkey: education, science, technology”, Baku, 2019; 13th International conference “Application of information and communication technologies”, Baku, 2019; 13th International conference on “Thermal engineering: theory and application”, Canada, 2020; 23rd International conference “WECONF-2020”, St. Petersburg, 2020; 3rd International scientific and practical conference “Energy saving and security of occupation: problems and prospects”, Kiev, 2020; International conference on communication and technology management, Vienna, 2021; International symposium on industrial research, Antalya, 2021; 11th International conference on “Theory and application of soft computing, verbal computing, perception and artificial intelligence”, Antalya, 2021; 2nd International scientific forum on computer and energy sciences, Almaty, 2021.

Publication of the results of the work. 101 scientific works, including 4 monographs were published in national and foreign scientific and technical publications on researches reflecting the content of the dissertation and their results.

The organization where the dissertation work is performed. The dissertation was completed at the Azerbaijan Technical University.

The structure and scope of the work. The dissertation consists of 393 pages of computer text in A4 format, including an introduction, seven chapters, a list of references and appendices, 173 figures, 35 tables (23 figures in appendices, 4 tables), a list of references used in 333 titles and 5 appendices. Introduction to the dissertation consists of 11 pages in A4 format, 1 Chapter 34 pages, 2 Chapter 77 pages, 3 Chapter 46 pages, 4 Chapter 25 pages, 5 Chapter 47 pages, 6 Chapter 43 pages, Chapter 7 consists of 32 pages, result 3 pages, list of used literature 39 pages, appendices 30 pages, list of abbreviations and symbols 1 page of computer text.

The main text of the dissertation (excluding pictures, tables, graphs, appendices and bibliography) - introduction 11 pages in A4 format (number of characters 22000), 1 Chapter 29 pages (number of characters 58000), 2 Chapter 51 pages (characters number 102000), 3 Chapter 29 pages (number of characters 58000), 4 Chapter 21 pages (number of characters 42000), 5 Chapter 20 pages (number of characters 40000), 6 Chapter 30 pages (number of characters 60000), 7 Chapter consists of 24 pages (number of characters 48000), the result is 3 pages (number of characters 6000) and a total of 218 pages (number of characters **436000**) of computer text.

MAIN CONTENT OF THE STUDY

The introduction substantiates the relevance of the dissertation topic, explains the purpose and main objectives of the research. The scientific novelty of the work and the practical significance of the obtained results were presented. Important results, suggestions and recommendations on the application of the teaching process and production are given.

The first chapter examines the current state of analysis and optimal synthesis of complex structural microwave radioengineering and telecommunication waveguide systems, identifies the main directions for improving the electrical, magnetic, technical, design and operational parameters and characteristics of microwave rectangular and circular waveguides.

In order to analyze the current state of the analysis of microwave radioengineering and telecommunication facilities, a review of world-class research in this field was given and it was determined that the nonlinearity of the environment inside rectangular and circular waveguides filled with air was not taken into account in theoretical or experimental studies.

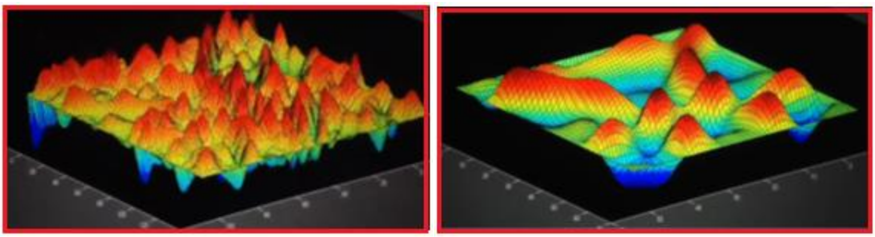
On the other hand, in order to analyze the current state of optimal synthesis of microwave radioengineering and telecommunication devices, a review of world research in this area was given and it was determined that the issue of their multi-criteria optimal synthesis has not been resolved yet. Thus, solving the problem of multi-criteria optimal synthesis of microwave rectangular and circular waveguides will allow to design and develop new physical models with optimal dimensions, while improving the electrical, magnetic, technical, design and operational parameters and characteristics of these devices.

Therefore, taking into account the non-linearity of the environment inside rectangular and circular waveguide devices, microwave is a new model with optimal dimensions, along with the solution of the problem of their multi-criteria optimal synthesis and specification of electromagnetic, design, technical and operational parameters and characteristics of these devices. and there is a need for development.

The second chapter deals with the modeling of complex structural microwave systems in a nonlinear environment.

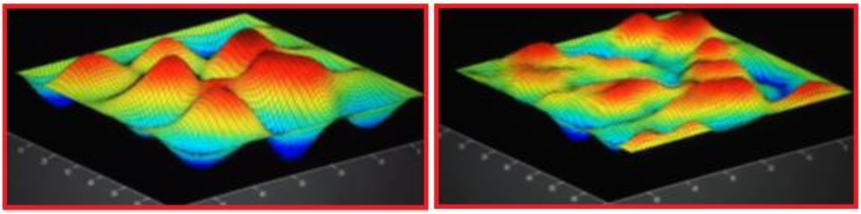
For the first time for a nonlinear medium, a mathematical expression was obtained between the relative dielectric constant and the electric field intensity, and based on this, effective algorithms were developed based on mathematical models of microwave rectangular and circular waveguides and finite differences and finite element numerical methods. As a result, taking into account the nonlinearity of the environment, the electromagnetic field intensities of *E*-type and *H*-type waves, H_{10} mode, microwave rectangular waveguide operating in the frequency range 4,9-7,05 *GHz* and microwave circular waveguide operating at 9 *GHz*, H_{11} mode were determined.

Based on the numerical results obtained, the *E*-type and *H*-type waveguide, H_{10} mode, microwave rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* (Figure 1, *a*, *b*) and microwave circular waveguide operating in H_{11} mode at 9 *GHz* (3*D* dependences of the intensity of the electromagnetic field on the length of Figure 2, *a*, *b*) are constructed. The 3*D* dependencies shown in Figures 1, 2, *a*, *b* determine the distribution of the electromagnetic field propagating within the microwave rectangular and circular waveguides and the relationship between the electromagnetic and design parameters of these devices.



***a*)** ***b*)**

Figure 1. Rectangular waveguide with frequency range of 4,9-7,05 *GHz* electric (*a*) and magnetic (*b*) for the *E*-type wave of the transmitter 3*D* model of the distribution of field intensities



***a*)** ***b*)**

Figure 2. Circular waveguide with frequency of 9 *GHz* for the *E*-type (*a*) and *H*-type (*b*) waves of the transmitter 3*D* model of the distribution of field intensities

At the same time, the dispersion compositions of different types (high and low types) of electromagnetic waves propagating in rectangular and circular waveguides in nonlinear media were studied here, and the effect of field intensities on the dispersion dependencies was shown.

As can be seen from the obtained curves, the propagation of radio waves in the non-linear medium in the selected ranges varies more sharply than in the linear medium.

In addition, in this chapter, the limit power, permissible power, attenuation coefficient, stagnant wave coefficient of the microwave path of a rectangular waveguide in the frequency range of 4,9-7,05 *GHz* for H_{10} mode of *E*-type (*TH*) and *H*-type (*TE*) waves, new mathematical expressions were obtained, taking into account the nonlinearity of the environment for the reflection coefficient, specific quality, phase and characteristic resistance of the reflection coefficient.

The third chapter presents the modeling, research, and results of complex structural microwave waveguide systems in a moving coordinate system in a nonlinear environment.

It is known that since the environment in which electromagnetic waves propagate is non-linear, the intensities of electric and magnetic fields within the studied waveguides must have different values. Therefore, it is necessary to use a moving coordinate system.

In this chapter, mathematical models of the electromagnetic field of a rectangular waveguide in the moving coordinate system have been developed.

- For H_{10} mode of *E*-type (*TH*) wave of microwave rectangular waveguide:

$$E_z'^{mn} = E_0 \sin\frac{m\pi x'}{a}\sin\frac{n\pi y'}{b}e^{-i\beta z}, \tag{1}$$

$$E_x'^{mn} = -iE_0\frac{\chi_x\left[\beta-(v/c^2)\omega\right]}{\chi^2\sqrt{1-(v/c^2)}}\cos\frac{m\pi x'}{a}\sin\frac{n\pi y'}{b}e^{-i\beta z}, \tag{2}$$

$$E_y'^{mn} = -iE_0\frac{\chi_x\left[\beta-(v/c^2)\omega\right]}{\chi^2\sqrt{1-(v/c^2)}}\sin\frac{m\pi x'}{a}\cos\frac{n\pi y'}{b}e^{-i\beta z}, \tag{3}$$

$$H_x'^{mn} = iE_0\frac{\varepsilon_0\chi_y(\omega-v\beta)}{\chi^2\sqrt{1-(v/c^2)}}\sin\frac{m\pi x'}{a}\cos\frac{n\pi y'}{b}e^{-i\beta z}, \tag{4}$$

$$H_y'^{mn} = -iE_0\frac{\varepsilon_0\chi_x(\omega-v\beta)}{\chi^2\sqrt{1-(v/c^2)}}\cos\frac{m\pi x'}{a}\sin\frac{n\pi y'}{b}e^{-i\beta z}, \tag{5}$$

$$H_z'^{mn} = 0, \tag{6}$$

- For H_{10} mode of *H*-type (*TE*) wave of microwave rectangular waveguide:

$$E_z'^{mn} = 0, \tag{7}$$

$$E_x'^{mn} = iH_0\frac{\mu_0\chi_y(\omega-v\beta)}{\chi^2\sqrt{1-(v/c^2)}}\cos\frac{m\pi x'}{a}\sin\frac{n\pi y'}{b}e^{-i\beta z}, \tag{8}$$

$$E_y'^{mn} = -iH_0\frac{\mu_0\chi_x(\omega-v\beta)}{\chi^2\sqrt{1-(v/c^2)}}\sin\frac{m\pi x'}{a}\cos\frac{n\pi y'}{b}e^{-i\beta z}, \tag{9}$$

$$H_x'^{mn} = iH_0\frac{\chi_x\left[\beta-(v/c^2)\omega\right]}{\chi^2\sqrt{1-(v/c^2)}}\sin\frac{m\pi x'}{a}\cos\frac{n\pi y'}{b}e^{-i\beta z}, \tag{10}$$

$$H_y'^{mn} = iH_0\frac{\chi_y\left[\beta-(v/c^2)\omega\right]}{\chi^2\sqrt{1-(v/c^2)}}\cos\frac{m\pi x'}{a}\sin\frac{n\pi y'}{b}e^{-i\beta z}, \tag{11}$$

$$H_z'^{mn} = H_0\cos\frac{m\pi x'}{a}\sin\frac{n\pi y'}{b}e^{-i\beta z}. \tag{12}$$

- For H_{11} mode of E-type (TH) wave of microwave circular waveguide:

$$E_z'^{nm} = J_n(\chi_{nm} r')\psi_n(\theta')\exp(-i\beta z'), \tag{13}$$

$$E_r'^{nm} = -i\frac{\beta - (v/c^2)\omega}{\chi_{nm}\sqrt{1-(v/c^2)}} J_n'(\chi_{nm} r')\psi_n(\theta')\exp(-i\beta z'), \tag{14}$$

$$E_\theta'^{nm} = -in\frac{\beta - (v/c^2)\omega}{\chi_{nm}^2 r'\sqrt{1-(v/c^2)}} J_n(\chi_{nm} r')\psi_n'(\theta')\exp(-i\beta z'), \tag{15}$$

$$H_z' = 0, \tag{16}$$

$$H_r'^{nm} = i\frac{n\varepsilon_0(\omega - v\beta)}{\chi_{nm}^2 r'\sqrt{1-(v/c^2)}} J_n(\chi_{nm} r')\psi_n'(\theta')\exp(-i\beta z'), \tag{17}$$

$$H_\theta'^{nm} = -i\frac{\varepsilon_0(\omega - v\beta)}{\chi_{nm}\sqrt{1-(v/c^2)}} J_n'(\chi_{nm} r')\psi_n(\theta')\exp(-i\beta z'), \tag{18}$$

- For H_{11} mode of H-type (TE) wave of microwave circular waveguide:

$$E_z'^{nm} = 0, \tag{19}$$

$$E_r'^{nm} = -i\frac{n\mu_0(\omega - v\beta)}{\chi_{nm}^2 r'\sqrt{1-(v/c^2)}} J_n(\chi_{nm} r')\psi_n'(\theta')\exp(-i\beta z'), \tag{20}$$

$$E_\theta'^{nm} = i\frac{\mu_0(\omega - v\beta)}{\chi_{nm}\sqrt{1-(v/c^2)}} J_n'(\chi_{nm} r')\psi_n(\theta')\exp(-i\beta z'), \tag{21}$$

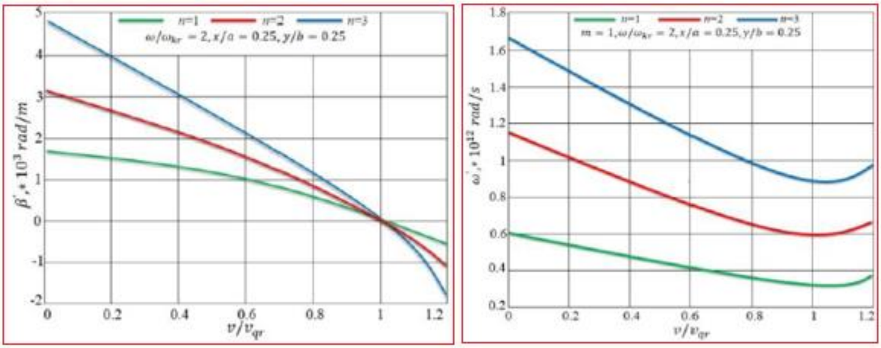
$$H_z'^{nm} = J_n(\chi_{nm} r')\psi_n(\theta')\exp(-i\beta z'), \tag{22}$$

$$H_r'^{nm} = -i\frac{\beta - (v/c^2)\omega}{\chi_{nm}^2\sqrt{1-(v/c^2)}} J_n'(\chi_{nm} r')\psi_n(\theta')\exp(-i\beta z'), \tag{23}$$

$$H_\theta'^{nm} = -in\frac{\beta - (v/c^2)\omega}{\chi_{nm}^2 r'\sqrt{1-(v/c^2)}} J_n(\chi_{nm} r')\psi_n'(\theta')\exp(-i\beta z'). \tag{24}$$

By solving the obtained equations (1)-(12) and (13)-(24), the dependence of the velocity of the coordinate system of the parameters β' and ω' on the coordinate system moving for the E-type (TH) wave of the microwave rectangular waveguide was established (Figure 3, *a*, *b*).

In this chapter, as well as the frequency dependence of the attenuation coefficient for H_{10} and E_{11} modes in microwave rectangular waveguides operating in the frequency range of 4,9-7,05 *GHz* and H_{11} and H_{01} in microwave circular waveguides with 9 *GHz* frequencies, including *s*-polarization and *p*-polarization in these transmitters, the speed dependence of the surface impedance calculation system for polarized electromagnetic waves was determined by accepting the conductivity of the internal conductive surface of the waveguides $\sigma = 5{,}8 \cdot 10^8 \, Sim/m$.

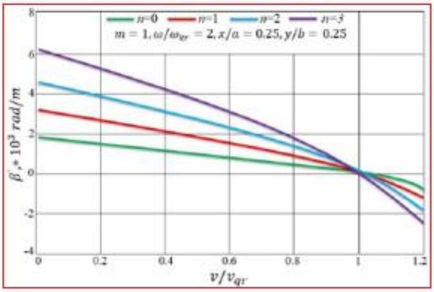


***a*)** ***b*)**

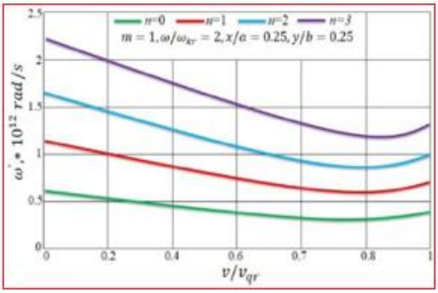
Figure 3. The dependence of the parameters β' (*a*) and ω' (*b*) on the velocity of the coordinate system in the coordinate system moving for the *E*-type wave of the microwave rectangular waveguide

The dependence of the parameters β' and ω' for the *H*-type wave of the microwave rectangular waveguide on the speed of the coordinate system is shown in Figure 4, *a*, *b*.

Thus, it is defined in this chapter: a) the smaller the wavelength of the excited oscillations, the more types of waves can be excited when the microwave transmits a rectangular waveguide; b) the largest crisis when microwave transmits a rectangular waveguide is the H_{10} wavelength. This wave is a low type or main type, ie a wave that carries information. All other waves are waves with shorter crisis lengths; c) in the case of a rectangular waveguide, the field is distributed differently, but waves of the same crisis length may be present (E_{11}-H_{11}, E_{21}-H_{21}).



a)



b)

Figure 4. The dependence of the parameters β' (*a*) and ω' (*b*) on the velocity of the coordinate system in the coordinate system moving for the *H*-type wave of the microwave rectangular waveguide

The fourth chapter is devoted to the modeling of microwave systems with complex structural mixed combinations. Here, a mathematical model of the surface impedance of an irregular and complex-walled rectangular waveguide was developed, and the problem of connecting them to each other by opening cracks of different sizes in the complex waveguide microwave paths was solved. At the same time, the problem of modeling the electromagnetic field in a switching device from a rectangular waveguide to a circular waveguide has been solved theoretically and experimentally. Thus, a circular waveguide was placed inside the rectangular waveguide, and in this complex waveguide system, the propagation of the electromagnetic wave and the coefficient of interaction were determined.

This chapter also discusses the electrodynamic modeling of a circular waveguide. Thus, the determination of the propagation constant and the structure of the electromagnetic field in the circular waveguide of the microwave is reduced to the following Helmholtz equations:

$$\nabla^2 E_Z + g^2 E_Z = 0, \qquad (25)$$

$$\nabla^2 H_Z + g^2 H_Z = 0. \qquad (26)$$

In this case, the following boundary conditions are included:

$$E_Z = 0, \tag{27}$$

$$\frac{\partial H_Z}{\partial n} = 0. \tag{28}$$

To solve this problem, an orthogonal coordinate was chosen so that their coordinate surface coincides with the surface of the circular waveguide.

The methods of collocation and finite differences were used to solve the boundary value problem (25), (26) and (27), (28).

In a cylindrical coordinate system, equations (25) and (26) can be written as follows:

$$\frac{\partial^2 E_Z}{\partial r^2} + \frac{1}{r} + \frac{\partial E_Z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_Z}{\partial \varphi^2} + gE_Z = 0, \tag{29}$$

$$\frac{\partial^2 H_Z}{\partial r^2} + \frac{1}{r} + \frac{\partial H_Z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 H_Z}{\partial \varphi^2} + gH_Z = 0. \tag{30}$$

Here E_Z and H_Z are understood as $E_Z = E_Z(r,\varphi)$ and $H_Z = H_Z(r,\varphi)$ respectively. The solution of these equations by the method of division into variables led to the following expressions:

$$E_Z(r,\varphi) = \sum_{m=0}^{\infty}\left[C_{Em}J_m(gr) + D_{Em}N_m(gr)\right]\times\left[A_{Em}\cos(m\varphi) + B_{Em}\sin(m\varphi)\right], \tag{31}$$

$$H_Z(r,\varphi) = \sum_{m=0}^{\infty}\left[C_{Hm}J'_m(gr) + D_{Hm}N'_m(gr)\right]\times\left[A_{Hm}\cos(m\varphi) + B_{Hm}\sin(m\varphi)\right], \tag{32}$$

where $J_m(gr),\ J'_m(gr)$ is a Bessel function or a cylindrical function of order m, $N_m(gr),\ N'_m(gr)$ is a Neumann function or a secondary cylindrical function, g is the number of transverse waves.

The cross-sectional area of a circular waveguide and its contour consists of two parts: the radius $r = a$ and the line L.

Given that the boundary conditions (27) and (28) are satisfied at arbitrary values of φ when $r = a$, we obtain

$$D_{Em} = -C_{Em}\frac{J_m(ga)}{N_m(ga)}, \tag{33}$$

$$D_{Hm} = -C_{Hm}\frac{J'_m(ga)}{N'_m(ga)}. \tag{34}$$

Let's accept the following substitutions:

$$Z_{Em}(gr) = J_m(gr)N_m(ga) - J_m(ga)N_m(gr), \tag{35}$$

$$Z_{Hm}(gr) = J'_m(gr)N'_m(ga) - J'_m(ga)N'_m(gr). \tag{36}$$

Then we will get

$$E_Z(r,\varphi) = \sum_{m=0}^{\infty} Z_{Em}(gr)\left[A_{Em}\cos(m\varphi) + B_{Em}\sin(m\varphi)\right], \tag{37}$$

$$H_Z(r,\varphi) = \sum_{m=0}^{\infty} Z_{Hm}(gr)\left[A_{Hm}\cos(m\varphi) + B_{Hm}\sin(m\varphi)\right]. \tag{38}$$

Here, the constants $C_{Em}/N_m(ga)$ and $C_{Hm}/J'_m(ga)$ are included in the coefficients A_{Em} and B_{Em}, A_{Hm} and B_{Hm}, respectively. The essence of the collocation method is as follows: the parameters A_{Em} and B_{Em} for the *E*-wave or the parameters A_{Hm} and B_{Hm} for the *H*-wave are selected so that the functions (37) and (38) meet the conditions (27) and (28), respectively.

The following new variance equations for *E*-type and *H*-type waves were obtained using the collocation method:

For *E*-type waves:

$$\left\|\left[Z_k(gr_i)\sin k\varphi\right]\right\| = 0, \tag{39}$$

$$\left\|\left[Z_k(gr_i)\cos k\varphi\right]\right\| = 0, \tag{40}$$

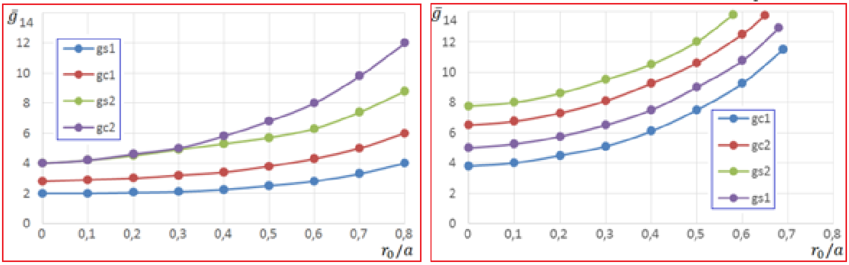
where $k = 1,2,\ldots,n -$ are the indices on row, $i = 1,2,\ldots,n -$ the indices on column, $n - L$ - the number of points on the boundary, $g -$ the number of transverse waves, and $r = a -$ the radius of the transmitter.

For *H*-type waves:

$$\left\|\left[\cos(k+1)_{\varphi i}\left(gZ'_{Hk}(gr_i) - \frac{k}{r_i}Z_{Hk}(gr_i)\right) + \cos(k-1)_{\varphi i}\left(gZ'_{Hk}(gr_i) + \frac{k}{r_i}Z_{Hk}(gr_i)\right)\right]\right\| = 0, \tag{41}$$

$$\left\|\left[\sin(k+1)_{\varphi i}\left(gZ'_{Hk}(gr_i) - \frac{k}{r_i}Z_{Hk}(gr_i)\right) + \sin(k-1)_{\varphi i}\left(gZ'_{Hk}(gr_i) + \frac{k}{r_i}Z_{Hk}(gr_i)\right)\right]\right\| = 0. \tag{42}$$

By solving the obtained equations (39)-(42), the transverse wave number and critical wavelength were determined, and on the basis of these estimates the dependence of the transverse wave number on the ratio of the cross-sectional dimensions of the circular waveguide (Figure 5, *a*, *b*) was established.



***a*)** ***b*)**

Figure 5. Dependencies of the transverse wave number g on the ratio of the cross-sectional area of the microwave circular waveguide r_0/a: a) in the case of *E*-type wave; b) in the case of *H*-type wave

If we extrapolate the obtained graphs to $r_0/a \to 0,$ areas, we can achieve the collection of solutions. Thus, for the *E*-type wave, the root $\bar{g}_{c1}$ will asymptotically approach the root of the E_{11}-type wave (3,832), $\bar{g}_{s1}-$ roots to E_{21}-type wave (5,52), $\bar{g}_{c2}-$ roots to E_{31}-type wave (6,38), $\bar{g}_{s2}-$ roots to E_{41}-type wave (7,588); for the *H*-type wave, the $\bar{g}_{c1}$ roots will asymptotically approach the root of the H_{21}-type wave (3,054), $\bar{g}_{c2}-$ roots will approach the H_{01}-type wave (3,832), $\bar{g}_{s1}-$ roots will approach the H_{11}-type wave (1,841), and $\bar{g}_{s2}-$ roots will approach the H_{31}-type wave (4,201).

In solving this problem, an orthogonal coordinate was chosen so that their coordinate surface coincides with the surface of the circular waveguide.

The fifth chapter deals with the experimental study of complex structural microwave systems in a non-linear environment. Here, the characteristics of the switching device from the microwave rectangular waveguide to the mouthpiece were determined experimentally by the device shown in Figure 6.

The measurement was performed using the following methodology. The microwave clistron generator is connected to the fuselage on the body. The receiving mouthpiece is placed at least 3 *m* away from the transmitting mouthpiece. Transmitter and receiver loudspeakers are placed along one axis. The signal from the output of the receiver mouthpiece is transmitted to the millivoltmeter of the indicator block.

Figure 6. Orientation diagram
a device designed for experimental determination

During the experimental study, the output voltage at the output of the receiver was measured by θ discrete variations of 1^0 angles in the vertical plane, and then normalized graphs of field orientation diagrams were constructed (Figure 7). Measurements were made in the range of -90^0 to $+90^0$ of θ relative to the axis of the mouthpiece.

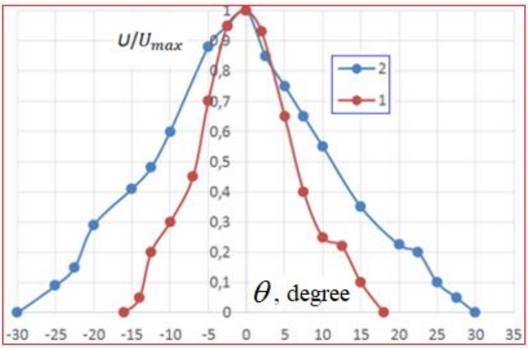


Figure 7. Field intensity of the loudspeaker orientation diagrams according to: 1-vertical plane; 2-horizontal plane

The measurement results of the modulus of transmission and reflection coefficients are shown in Figure 8.

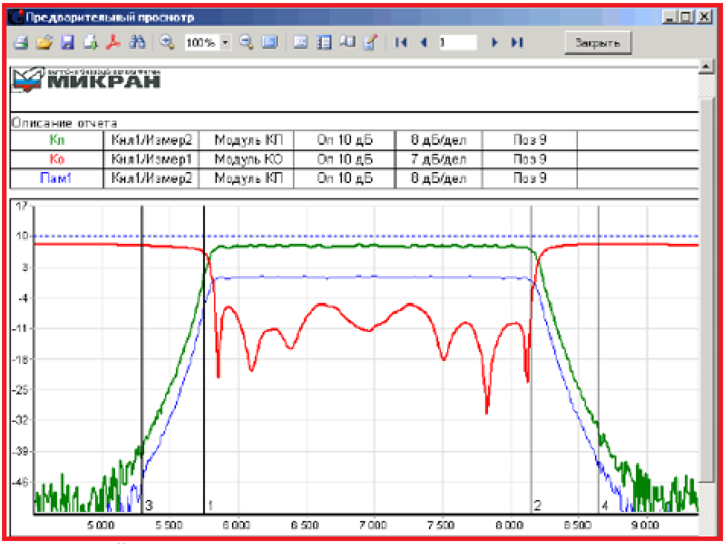


Figure 8. Modules of transmission and reflection coefficients results obtained on a computer

A waveguide measuring line was used to experimentally determine the parameters of the electromagnetic field of the transmitters in the microwave range. The block diagram of the proposed measuring device for the study of the electromagnetic field in the microwave waveguide is shown in Figure 9.

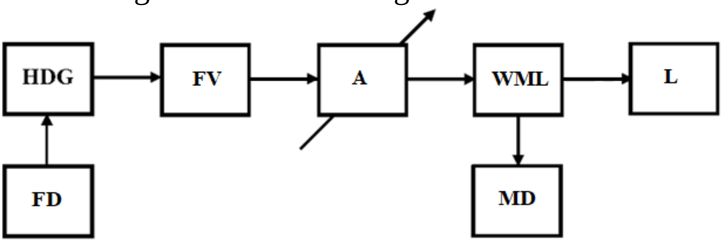


Figure 9. Block diagram of a measuring device for the study of the electromagnetic field in the microwave waveguide

All nodes included in the waveguide of the measuring device are made on the basis of microwave rectangular waveguide with a cross-sectional area of 40x20 *mm*. The electromagnetic wave is transmitted to the line via a Hann diode microwave generator (HDG). This generator is fed through a feed device (FD). A ferrite valve (FV) is placed at the inlet of the measuring device to coordinate the load (L) inlet. After the attenuator (A) used to regulate the power level of the wave, a waveguide measuring line (WML) is placed. With the help of (WML), the stagnant wave coefficient and electromagnetic field distribution in (L), as well as the values of the electric and magnetic field intensities of the waveguide were determined. The measuring device (MD) connected to the output of the detector of the (MD) is a constant voltage microvoltmeter.

As a result of the measurements, experimental values of the electromagnetic field intensities of a rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and a circular waveguide operating in the frequency range of 9 *GHz* were determined.

The scheme shown in Figure 10 is proposed for the measurement of power in both waves in a two-mode microwave transmitter. Here, the input of the measuring section (1) of a dual-mode microwave transmitter consisting of a galvanomagnetic converter (2) is supplied with microwave power for each of the H_{10} and H_{20} module waves. The measuring section is connected to the load (3). In this case, the electromagnetic field in the measurement section is described in the form of a superposition of incident and reflected waves. The voltage was measured with a galvanomagnetic transducer and this voltage was taken in proportion to the power flux density of the final electromagnetic field. The signal passes through the analog-digital converter (4) and enters the computer (5) for processing, and the processing takes place. Thus, for each wave type, the power passing through the cross-sectional area of the dual-mode microwave waveguide was determined.

The energy transfer of an electromagnetic field through a waveguide in the microwave range is characterized by the value of current and voltage. One of the most important issues is the measurement of dispersion and attenuation during the transmission of electromagnetic waves through microwave waveguide. Another key parameter of the transmission path is the wave resistance (full resistance or impedance). This resistance is determined by the ratio of the transverse concentrations of the electric and magnetic field intensities.

For a non-uniform and nonlinear path, the resistance has the same value along the entire cross section of the waveguide. The ratio of the resistances of the various elements of the tract indicates the efficiency of energy transfer. Thus, the maximum transfer of power occurs when the wave resistances of all elements are equal. The fact that the wave resistances have different values leads to reflection. From the above it can be concluded that the main parameters of the microwave path are dispersion, attenuation and impedance. Therefore, for the measurement of these parameters, an experimental device was proposed to measure the dispersion, attenuation and impedance on this device.

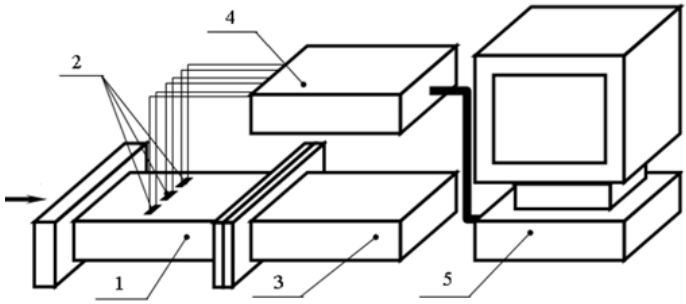


Figure 10. Schematic of a device for measuring power in the case of H_{11} and H_{10} waves in a two-mode microwave waveguide

This chapter also provides a comparative analysis of the results obtained from the experimental study of microwave rectangular and circular waveguides by numerical methods, and an error estimate. It was determined that the relative error between the theoretical and experimental results for field intensities is up to 4%, and the relative error for other parameters of the microwave tract is up to 1%. A comparison of the values of the experimentally and theoretically determined parameters of the microwave tract of a rectangular waveguide operating on the H_{10} wave is given in Table 1.

Table 1

Rectangle operating in H_{10} mode experimentally and theoretically determined values of the parameters of the microwave path of the waveguide

Parameter name and unit	Experimental	Theory
Limit power, P_d, *Vt*	4010,5	4000
Permissible power, P_{bur}, *Vt*	1211	1200
Extinction coefficient, α, *dB/m*	0,0201	0,0203
Stagnant wave coefficient, K_{dd}	1,021	1,02
Coefficient of repulsion, Q	0,0098	0,0099
Special quality, Q_0	4497,2	4490
Phase of the refractive index, φ, *rad/m*	39,9π	39,8π
Characteristic resistance, Z_H, *Ohm*	376,6	376,7

As can be seen from Table 1, the relative error value for all parameters does not exceed 1%. This, in turn, proves the validity of the expressions obtained taking into account the nonlinearity of the environment and the theoretically determined results based on these expressions.

The sixth chapter is devoted to the optimal synthesis of complex structured microwave systems in a nonlinear environment. For this purpose, the problem of multi-criteria parametric optimization of devices with microwave range has been solved. The criteria for the optimal synthesis of microwave rectangular and circular waveguides were selected as follows. It is assumed that the operator L is the analysis operator of microwave rectangular and circular waves. The operator L is characterized by the intensities of the electric and magnetic fields of these devices *E, H (a, b, r)* and the propagation constant of the waves $\gamma(f)$. Where f is the normalized frequency of the rectangular or circular waveguide.

The following functionality is offered for rectangular and circular waveguides.

$$\gamma(f) = L[E, H(a,b,r)]. \tag{43}$$

Let us denote by $\tilde{\gamma}(f)$ the required dependence of the normalized propagation constant of the waves. The similarity of functions

$\gamma(f)$ and $\tilde{\gamma}(f)$ was determined using $F = \{L[E, H(a,b,r)], \tilde{\gamma}\}$ evaluation functions as follows:

$$F = \{L[E, H(a,b,r)], \tilde{\gamma}\} = \max_{f \in [f_1 f_2]} \left| L\left[E, H\left(a,b,r\right)\right] - \tilde{\gamma} \right| \quad (44)$$

or

$$F = \{L[E, H(a,b,r)], \tilde{\gamma}\} = \int_{f_1}^{f_2} \sigma(f)(L[E, H(a,b,r)] - \tilde{\gamma})^2 df, \quad (45)$$

where f_1, f_2 are the operating frequency range of the rectangular and circular waveguides.

The inclusion of $\sigma(f)$ weight functions allows for the accurate realization of $\tilde{\gamma}(f)$ in different sub-ranges of the f range. The physical and design parameters of the devices were taken into account when selecting methods for solving the optimal synthesis problem.

For rectangular and circular waveguides, the following are:

$$0 < E_{\min}, H_{\min} \le E, H(a,b,r) \le E_{\max}, H_{\max}, \quad (46)$$

$$E, H(a,b,r) \in M, \quad (47)$$

$$N^P[E, H(a,b,r)] = F\{L[E, H(a,b,r)] - \tilde{\gamma}\} + pT[E, H, (a,b,r)],$$

$$F = \{L[E, H(a,b,r)], \tilde{\gamma}\} \le \Delta. \quad (48)$$

Under these conditions, optimal synthesis of microwave rectangular and circular waveguides was performed using Empipe 3*D* and HFSS complexes, and spatial models of optimized microwave rectangular and circular waveguides (Figure 11 and Figure 13) and frequency characteristics (Figure12 and Figure 14) were obtained.

Thus, after the optimal synthesis process, a new physical model of the microwave rectangular waveguide was obtained. After optimization, its constructive dimensions were 47,55x22,15 *mm*.

At the same time, it was determined that the basis for the optimal synthesis of devices in the microwave range is the search for the optimal structure of the electromagnetic field of these devices. It depends on the choice of criteria for the optimality of the structure, the nonlinearity of the environment, the types of waves. Unsatisfactory selection of the optimal structure of the electromagnetic field of rectangular and circular waveguides with microwave range cannot be improved by compensating in the process of parametric optimization.

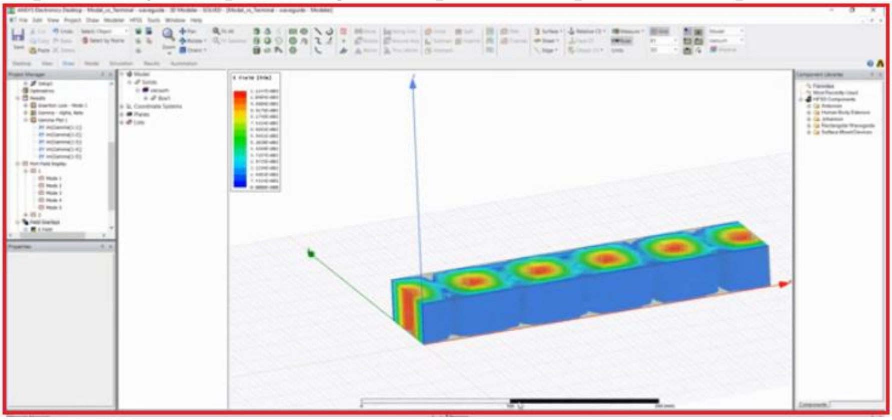


Figure 11. Optimized spatial model of the microwave rectangular waveguide

The operating frequency range *f* = 4,94-5,99 *GHz* was selected according to these dimensions. As can be seen, the attenuation coefficient was reduced from 0,0431 *dB/m* to 0,0201 *dB/m* as the frequency range of the microwave rectangular waveguide was reduced after optimization. For the microwave circular waveguide, the operating frequency was reduced from 9 *GHz* to 7,5 *GHz*. This, in turn, allowed the attenuation coefficient to be reduced from 0,0527 *dB/m* to 0,0211 *dB/m*.

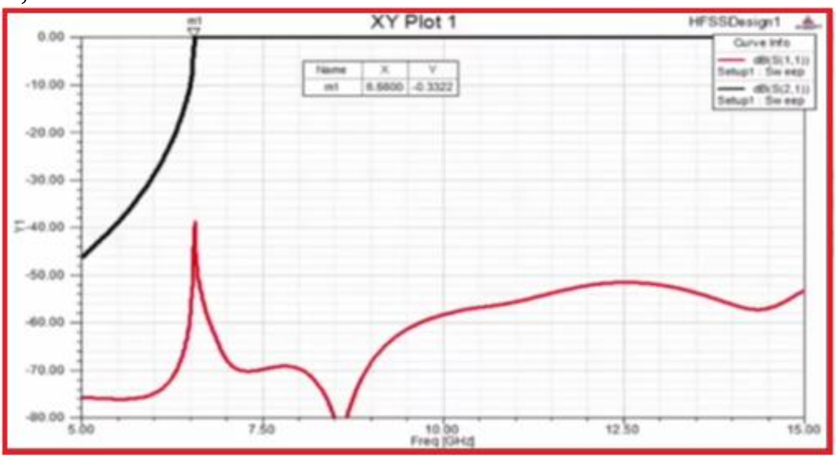


Figure 12. Optimized rectangular waveguide frequency characteristic

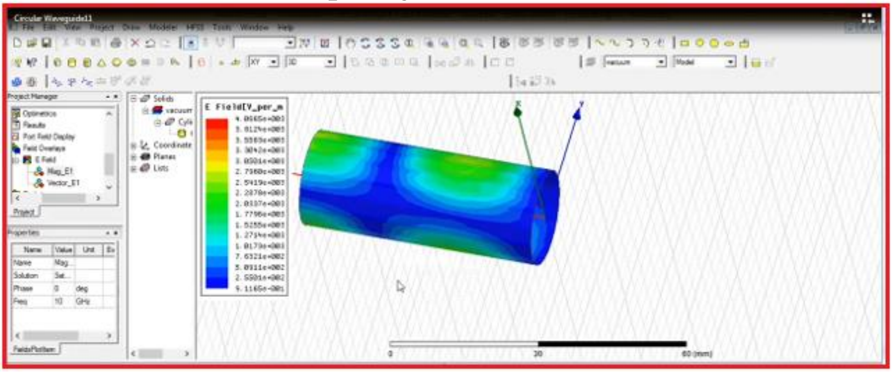


Figure 13. Optimized spatial model of the microwave circular waveguide

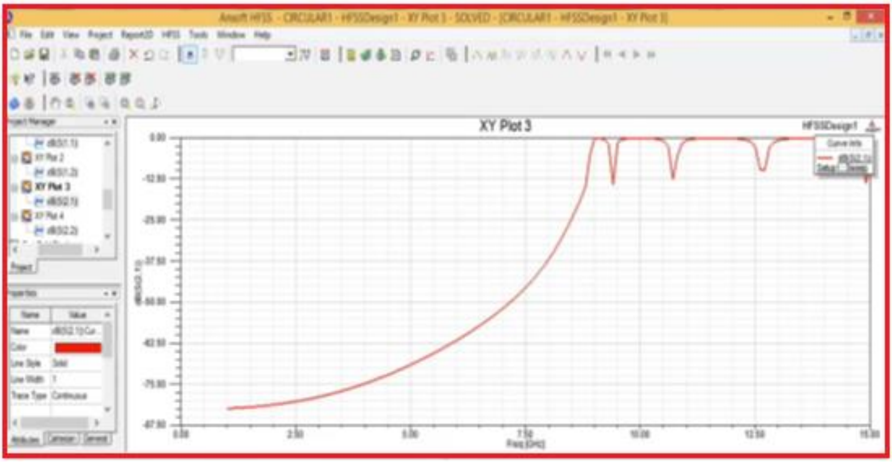


Figure 14. Optimized circular waveguide frequency characteristic

As a result of the research, the Sumgait-Gilazi main radio relay line with a height of 37 *m* in the Sumgait transmission part and a height of 40 *m* in the Gilazi receiver section was replaced by a wave transmission system with a cross-sectional area of 40x20 *mm* and a width of 47,55x22,15 *mm*. This, in turn, allowed the decommissioning of 12 microwave amplifiers in the transmission part and the annual economic benefit was 116842 AZN. The main factors in achieving economic efficiency were the saving of electricity consumption and decommissioning of the equipment used in the main radio relay line.

After optimization, the parameters of microwave rectangular and circular waveguides are given in Table 2 and Table 3.

Table 2

Parameters of microwave rectangular waveguide obtained after optimization

Microwave rectangular waveguide parameters before optimization			
Working frequency range, *GHz*	The cross-sectional area, *mm*		Extinction coefficient for brass waveguide, *dB/m*
	a	*b*	
4,9-7,05	40	20	0,0431
Parameters of microwave rectangular waveguide after optimization			
3,94-5,99	47,55	22,15	0,0201

In the process of optimal synthesis, parametric optimization of rectangular and circular waveguides with *E*-type and *H*-type waveguide microwave bands was performed in two stages. In the first stage, the fulfillment of technical requirements was assessed by creating a normal (initially given) rectangular and circular waveguide. In the second stage, based on a higher-level model, its parameters were specified.

Table 3

Parameters of microwave circular waveguide obtained after optimization

Microwave circular waveguide parameters before optimization		
Working frequency, *GHz*	Diameter, *d*, *mm*	Extinction coefficient for brass waveguide, *dB/m*
9	50	0,0422
Parameters of microwave circular waveguide after optimization		
7,5	60	0,0211

Thus, on the basis of optimized transmitters, a new waveguide system connecting the transmitter and the antenna was developed and implemented in order to improve the quality of transmission in television towers (Figure 15).

This chapter also describes the construction of at least two models of rectangular and circular waveguides - basic (approximate, single-wave) and auxiliary (specified) models for the optimal organization of the synthesis process.

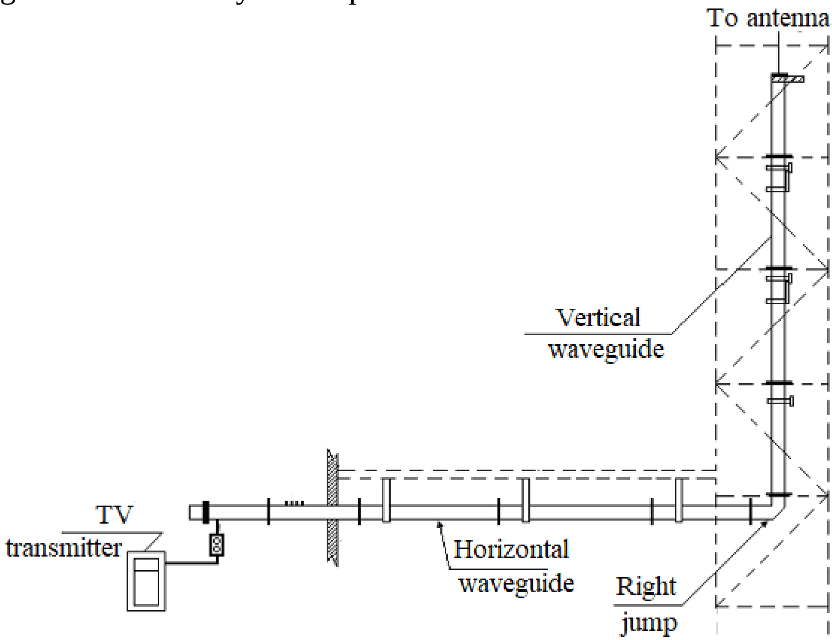


Figure 15. New waveguide system developed to connect the transmitter and antenna in television towers

The seventh chapter is devoted to the modeling of specially designed microwave systems. Here, the modeling of the electromagnetic field of a rectangular waveguide with slit side walls was performed (Figure 16).

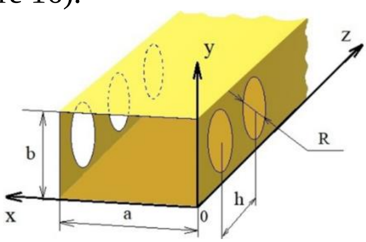


Figure 16. Side wall with circular slit rectangular waveguide

Thus, in this chapter, the variance equation for a rectangular waveguide with an infinite number of cracks in a small wall has been developed.

$$\sum_{k=0}^{\infty}\left\{\left[\left(\tilde{z}_{p0}^{+}+\tilde{z}_{p0}^{-}\right)U_k^{(s)}-(1+\delta_{nk})\delta_{nk}\cdot V_k^{(s)}\right]A_k^{(s)}+\frac{1}{2}\sum_{k=0}^{\infty}\left(\tilde{z}_{pr}^{+}U_k^{(s-r)}A_k^{(s-r)}+\tilde{z}_{pr}^{-}U_k^{(s+r)}A_k^{(s+r)}\right)\right\}=0, \quad (49)$$

where $n=0,1,2,\ldots;s=0,\pm1,\pm2,\ldots;p=|n-k|;\delta_{nk}-$ Kroneker symbol.

The effective surface impedance was calculated for the structure shown in Figure 16 and the dispersion characteristics were obtained depending on the value of the effective surface impedance and the wavelength (Figure 17 and Figure 18).

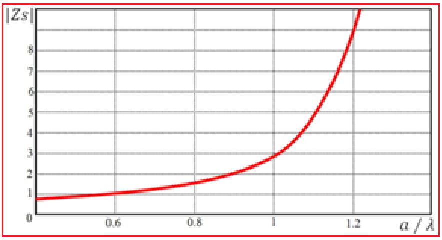


Figure 17. $|Z_{seff}|$ **modulus of effective impedance** a/λ **wavelength dependence**

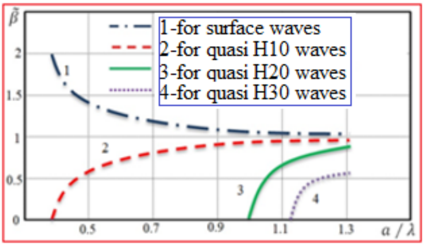


Figure 18. Dependencies of $\tilde{\beta}(a/\lambda)$ **normalized propagation constants of surface and volume waves**

Figure 18 shows that in such an microwave structure, both volumetric and surface waves can propagate, and when two impedance wall waves are transmitted, two surface waves can propagate. As can be seen from the graphs, an increase in the modulus of effective impedance leads to an increase in the propagation constant.

Quantitative analysis was also performed for the impedance of the two walls of the waveguide. Calculations have shown that it is possible to propagate two transverse surface waves in this structure. Figure 19 shows $\tilde{\beta}(|Z_{seff}|)$ dependencies for a two-impedance wall transmitter in $a/\lambda=0{,}8$ cases.

It should be noted that in $Z_{seff}\to 0$ cases the quasi H_{10} wave passes to the H_{10} wave. At this time, surface waves appear. At the same time, Figure 19 shows that at some values of Z_{seff}, the volume wave (curve

1) is interrupted. As a result of its increase, the value of β propagation constants decreases. In this case, one of the surface waves (curve 3) is inclined towards the unit, and the other wave passes from the surface wave to the volume wave (curve 2).

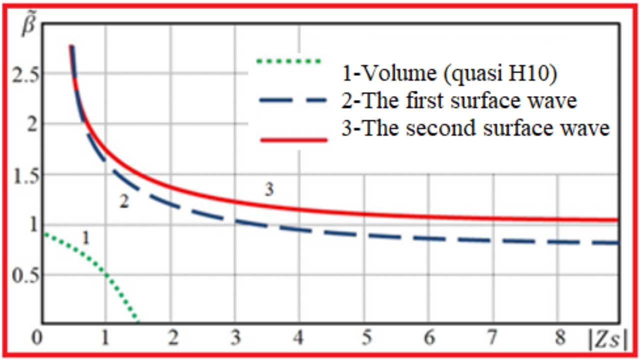


Figure 19. $a/\lambda = 0{,}8$ **in the case of two impedance walls** $\tilde{\beta}(|Z_{seff}|)$ **dependencies for the waveguide: 1 - volume (quasi** H_{10}**) wave; 2 - the first surface wave; 3 - second surface wave**

In this chapter, the following variance equation is obtained for the propagation coefficient of electromagnetic waves of a dielectric waveguide with a circular cross section shown in Figure 20, and the radius dependence of the propagation coefficient is established (Figure 21).

$$\Delta(\gamma) \equiv \left(\varepsilon_2 + \chi\Psi\big|_{r=R_2-0}\right)\Psi_1(R_2-0) - \gamma\frac{\varepsilon_3}{k_3}\frac{K_1(k_3R_2)}{K_0(k_3R_2)}\Psi_2(R_2-0). \quad (50)$$

where $\gamma -$ spread constant, $\chi -$ is the nonlinearity coefficient.

In the fourth paragraph of this chapter, new mathematical models for TE and TM type normal waves of the electromagnetic field of a rental rectangular waveguide with infinite ideal walls located at a certain distance from each other are developed:

$$\int_0^{z_0}\int_0^{a}\frac{1}{\mu}rot\mathbf{E}^*rot\mathbf{E}dxdz + \frac{\omega}{c}\int_c^{z_0}\int_0^{a}\frac{\chi}{\mu}\mathbf{E}rot\mathbf{E}^*dxdz + \frac{\omega}{c}\int_0^{z_0}\int_0^{a}\frac{\chi}{\mu}\mathbf{E}^*rot\mathbf{E}dxdz - $$
$$-\frac{\omega^2}{c^2}\int_0^{z_0}\int_0^{a}\left(\varepsilon - \frac{\chi^2}{\mu}\right)\mathbf{E}^*\mathbf{E}dxdz - \int_0^{a}\frac{1}{\mu}\left[e_z, \mathbf{E}^*\right]\left\{rot\mathbf{E}\Big|_{z=0}^{z=z_0} + \frac{\omega}{c}\chi\mathbf{E}\Big|_{z=0}^{z=z_0}\right\} = 0. \quad (51)$$

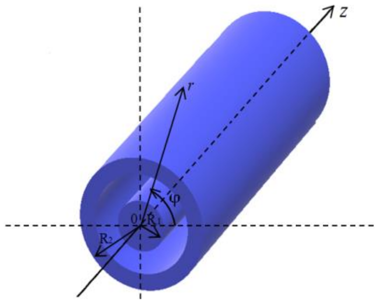


Figure 20. Circular cross section having a dielectric waveguide

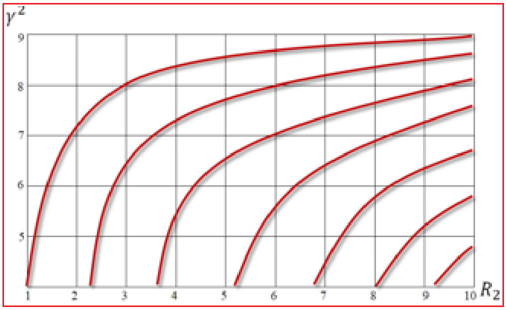


Figure 21. Dependence of the propagation constant γ^2 on the radius R_2: $\varepsilon_1 = 4, \varepsilon_2 = 9, \varepsilon_3 = 1, R_1 = 2{,}2 \prec R_2 \prec 12, \chi = 0, k_0 = 1$

Mathematical models obtained using the finite element method were solved and the distributions of the field components within the waveguide were constructed for different values of the roughness parameter of the medium (Figure 22 and Figure 23).

- In case of *TE* type wave:

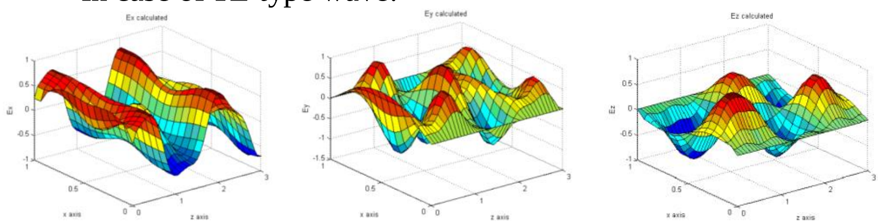


Figure 22. Inside the waveguide in case $\chi = 0{,}8$ field components

- In case of *TH* type wave:

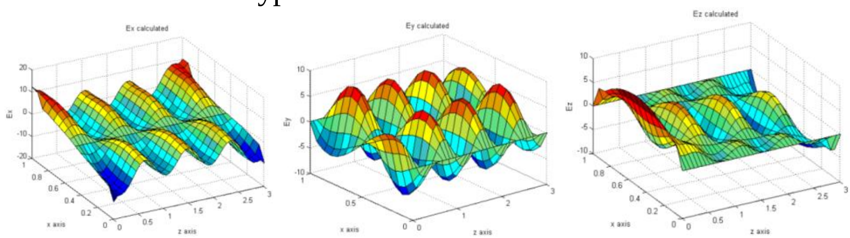


Figure 23. Inside the waveguide in case $\chi = 0{,}8$ field components

The analysis of the field components showed that the field in the kiral region of the waveguide is a hybrid. As a result, such a system can perform the function of a converter to convert one type of wave into another type of wave.

RESULTS

1. Based on the analysis of the current state of analysis and optimal synthesis of microwave devices, it was determined that in real practice the environment behaves as a non-linear environment, so for the analysis and optimal synthesis of microwave rectangular and circular waveguides, the existing theory needs to be reworked.

2. For the first time, an analytical expression was obtained between the electric field intensity and the relative dielectric constant of rectangular and circular waveguides, taking into account the nonlinearity of the medium. This analytical expression is of great theoretical and practical importance, as well as the basis for the design of radioengineering and telecommunication systems of different frequency bands for the transmission of information over long distances.

3. Non-linear environment, taking into account the types of waves. Cartesian and cylindrical coordinate systems of electromagnetic field of rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and circular waveguide operating in the frequency range of 9 *GHz*. Effective algorithms have been proposed for this purpose, which have allowed to improve the electrical, magnetic, structural and operational parameters and characteristics of rectangular and circular waveguides, and to minimize the extinction coefficient.

4. 3*D* models of distribution of electromagnetic field intensities in the elementary regions of rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* and circular waveguide operating in the frequency range of 9 *GHz* for *E*-type and *H*-type waves were developed, the dispersion compositions of electromagnetic waves, the effect of intensities on the variance dependencies is shown.

5. For non-linear medium *E*-type (*TH*) and *H*-type (*TE*) waves for H_{10} mode in the frequency range of 4,9-7,05 *GHz* microwave rectangular waveguide transmission path limit power, allowable power, attenuation coefficient, new mathematical expressions were obtained for parameters such as stagnant wave coefficient, reflection coefficient, specific quality, phase of reflection coefficient and characteristic resistance. At the same time, a new mathematical expression was obtained that allows to determine the surface impedance of a rectangular waveguide with irregular walls with any accuracy. It has been shown that the new mathematical expressions obtained for the microwave path of a rectangular waveguide with an irregular wall and a nonlinear environment can also be successfully applied in the design of more complex waveguide systems.

6. Experimental devices and functional schemes for measuring the parameters of the microwave path of rectangular and circular waveguides, as well as electric and magnetic fields in the non-linear state of the medium have been proposed and the parameters of waveguides have been determined experimentally. A comparison of theoretical and experimental results of the intensities of electric and magnetic fields showed that the relative error for these parameters is 4%, and for other parameters of the microwave path is 1%. This proved the adequacy of the theoretical and practical results obtained.

7. Experimental values of the intensity of electric and magnetic fields of a rectangular waveguide operating in the frequency range of 4,9-7,05 *GHz* for *E*-type and *H*-type waves, a circular waveguide operating in the frequency range of 9 *GHz*, its cross-sectional length, variance dependence, microwave extinction dependence has been established. These dependencies allow to create a visual image of the electromagnetic field propagated within the studied devices and other parameters of the microwave path.

8. It was determined that the basis for the optimal synthesis of microwave range devices is the search for the optimal structure and design dimensions of the electromagnetic field of these devices. It also depends on the choice of optimality criteria, the nonlinearity of the environment, the type of waves.

9. It was determined to perform parametric optimization of rectangular and circular waveguides with *E*-type and *H*-type waveguide microwave range in two stages. In the first stage, the fulfillment of technical requirements was assessed by creating a rectangular and circular waveguide to be optimized, and in the second stage, its parameters were specified based on a higher-level model, and the issue of minimizing the maximum function was solved.

10. In H_{10} and H_{11} wave modes new algorithms for optimal synthesis of microwave range rectangular and circular waveguides are given, their advantages are substantiated and parametric analysis and structural optimization of these devices are performed using HFSS, Empipe 3*D* software complexes. developed and improved their constructive, electrical parameters.

11. In order to improve the quality of broadcasting in the Television Broadcasting and Satellite Communications Production Union of the Ministry of Transport, Communications and High Technologies of the Republic of Azerbaijan on the basis of developed waveguides, a new waveguide system was proposed. It was reduced from 0,0431 *dB/m* to 0,0201 *dB/m*, and for circular waveguides from 0,0422 *dB/m* to 0,0211 *dB/m*, which means that the information transmitted from the transmitter to the receiver is longer. allowed the transmission.

12. The obtained results were applied on the Sumgait-Gilazi main radio relay line with the length of 41,8 *km* in the Television Broadcasting and Satellite Communications Production Union of the Ministry of Transport, Communications and High Technologies of the Republic of Azerbaijan. Thus, by increasing the cross-sectional area of the rectangular waveguide system, its operating frequency range was reduced to 3,94-5,99 *GHz*, which allowed to reduce the signal attenuation in the transmission of information in the waveguide system by more than 2 times. As a result of the research, the Sumgait-Gilazi main radio relay line with a height of 37 *m* in the Sumgayit transmission part and a height of 40 *m* in the Gilazi receiver section was replaced by a wave transmission system with a cross-sectional area of 40x20 *mm* and a width of 47,55x22,15 *mm*. This, in turn, allowed the decommissioning of 12 microwave amplifiers in the

transmission part and the annual economic benefit amounted to 116842 AZN. The main factors in achieving economic efficiency were energy savings and decommissioning of equipment used in the main radio relay line.

The following main scientific works on the topic of the dissertation have been published:

1. Исламов, И.Дж. Алгоритмизация численного расчета электромагнитных полей СВЧ элементов и устройств // Материалы НТК «Связь и наука», Министерство Связи, – Баку: – 2002, – с. 42-43.
2. Исламов, И.Дж. Численный анализ рассеяние электромагнитных волн волновода связи сантиметрового диапазона при режиме неоднородности и нелинейности среды // Материалы НТК «Связь и наука», – Министерство Связи, – Баку: – 2002, – с. 40-41.
3. Исмибейли, Э.Г., Исламов, И.Дж. Математические модели электромагнитного поля прямоугольного волновода с воздушным заполнением при нелинейной трактовке, используемых в системах связи // Труды 4-ой международной НТК «Электроника и информатика-2002», – ч. 2, – Московский Государственный Институт Электронной Техники, – Москва: – 19-21 ноябрь, – 2002, – с. 186-188.
4. Исламов, И.Дж. Моделирование электромагнитного поля полоскового СВЧ устройства методом конечных элементов // Труды республиканской конференции «Современные проблемы информатизации, кибернетики и информационных технологий», – Баку: – 2003, – т. 2, – с. 88-90.
5. Исламов, И.Дж. Новые математические модели электромагнитного поля прямоугольного волновода с воздушным заполнением при учете нелинейных свойств среды // Материалы РНТК, «Радиотехника и связь», – Баку: – 2003, – с. 13-25.
6. Исламов, И.Дж. Улучшенные модели расчета магнитного поля СВЧ прямоугольного волновода с учетом нелинейных свойств среды // – Баку: Техника, – 2003. №3, (16), – с. 60-69.

7. Исламов, И.Дж. Численное моделирование электрического поля прямоугольного волновода при нелинейной трактовке // “Heydər Əliyev və Azərbaycanda elmi-texniki tərəqqi” mövzusunda professor-müəllim heyəti və aspirantların Respublika konfransının materialları, – Bakı: – 2003, – s. 23-28.
8. Исмибейли, Э.Г., Исламов, И.Дж., Газиев, Ю.Г. Математическое моделирование и алгоритмизация расчета электромагнитных полей волноводов СВЧ диапазона // Труды 4-ой МНТК «Современные информационные и электронные технологии-2003», – Одесса, – 19-23 май, – 2003, – с. 57.
9. Islamov, I.J. Numerical method for analysis of electromagnetic field in microwave waveguide // 4th International Conference on Antenna Theory and Techniques, – Sevastopol, – 9-12 September, – 2003, – pp. 729-731.
10. Исламов, И.Дж. Расчет магнитного поля сверхвысокочастотного (СВЧ) волновода прямоугольного сечения с воздушным заполнением, работающего на частотах 4,9-7,05 ГГц // – Баку: Известия НАН Азербайджана. Серия физико-математической и технической наук, Элм, – 2003. №2, – т. 13, – с. 142-150.
11. Исламов, И.Дж. Оценка погрешности метода конечных элементов при расчете электрического поля прямоугольного волновода с воздушным заполнением // Труды юбилейной МНТК «Информационные и электронные технологии в дистанционном зондировании», посвященной 70-летию академика А.Ш.Мехтиева, – Баку: – 20-23 декабрь, – 2004, – с. 197-200.
12. İsmibəyli, E.Q. Elektron kvant cihazları və ifrat yüksək tezlikli qurğular. Dərslik. / E.Q.İsmibəyli, R.M.Rəhimov, İ.C.İslamov, – Bakı: Adiloğlu nəşriyyatı, – 2004, – 262 s.
13. Исламов, И.Дж. Численное моделирование и экспериментальное исследование электрического поля прямоугольного волновода при нелинейной трактовке // Баку:

Известия НАН Азербайджана, Серия физико-мат. и тех. наук, – 2004. №2, – т. 24, – с. 48-57.
14. Исмибейли, Э.Г., Исламов, И.Дж., Набиев, Г.Ш. Обобщенные математические модели электромагнитного поля полого круглого волновода // Баку: Ученые записки АзТУ, – 2004. №2, – т. 13, – с. 16-21.
15. Исламов, И.Дж. Электродинамический анализ сложных трехмерных волноводных СВЧ структур с помощью метода конечных разностей // Ümummilli lider Heydər Əliyevin Azərbaycan Respublikasının rəhbərliyinə gəlməsinin 36-cı ildönümünə həsr olunmuş beynəlxalq elmi-praktiki konfransın materialları, – Sumqayıt: – 2005, – s. 343-347.
16. Исламов, И.Дж., Аббасов, А.М. Измерение параметров электромагнитного поля в полом круглом волноводе // Материалы конференции АзТУ, – Баку: – 2005, – т. 2, – с. 33-36.
17. Исламов, И.Дж., Панычев, А.И. Математическая модель возбуждения электромагнитного поля системой нелинейной образований на клине // Труды пятой МНТК «Микроэлектронные преобразователи и приборы на их основе», – Баку-Сумгаит: 2005, – 5-8 декабрь, – с. 50-54.
18. İsmibəyli, E.Q., İslamov, İ.C. EHM-in tətbiqilə İYT element və qurğuların hesabatının alqoritmizasiyası, modelləşdirilməsi üçün ədədi-analitik üsulların işlənib hazırlanması // Dövlət büdcəli ETİ, – Bakı: – 2005, – 38 s.
19. Исламов, И.Дж. Новый подход к определению потенциала электрического поля, создаваемого заданным распределением в пространстве электрических зарядов // – Баку: – Известия НАН Азербайджана, серия физ.-мат. и технических наук, – 2005. №5, – с. 205-214.
20. Исламов, И.Дж. Численное моделирование электромагнитных полей в сверхвысокочастотных элементах и устройствах / И.Дж.Исламов. – Баку: Элм, – 2005. – 250 с.
21. Исламов, И.Дж. Критерии оптимальности синтеза СВЧ устройств // Материалы конференции АзТУ, – Баку: – 2005, – т. 2, – с. 31-33.

22. Исламов, И.Дж. Математические модели затухание при распространении электромагнитных волн в средах с конечной проводимостью // – Баку: – Ученые записки АзТУ, – 2005. №3, – с. 21-24.
23. Исмибейли, Э.Г., Исламов, И.Дж., Аббасов, А.М. Расчет числа возбуждаемых типов волн прямоугольного полого волновода для произвольной частоты // – Баку: – Ученые записки АзТУ, – 2005. №4, – с. 30-31.
24. Islamov, I.J., Mammadov, A.H. Modeling of an electromagnetic field of rectangular waveguide at nonlinearity of environment // Beynəlxalq ETK-ın materialları, – Bakı: – 2005, – s. 76-83.
25. Исламов, И.Дж. Трехмерное электродинамическое моделирование электромагнитного поля круглого волновода с помощью HFSS // Труды пятой международной конференции «Микроэлектронные преобразователи и приборы на их основе», – Баку-Сумгаит: – 2005, – 5-8 декабрь, – с. 58-61.
26. Islamov, I.J. Application of finite elements method by calculating electric field of hollow rectangular waveguide // – Bakı: AzTU-nun elmi əsərləri, – 2005. №4, – s. 35-38.
27. İsmibəyli, E.Q. Elektrodinamika və radiodalğaların yayılması. Dərslik. / E.Q.İsmibəyli, İ.C.İslamov – Bakı: Elm, – 2006. – 450 s.
28. İslamov, İ.C. Rabitə vasitələrinin elektromaqnit şüalanmasının insana təsirinin analizi // – Bakı: AzTU-nun elmi əsərləri, – 2006. №4, – s. 16-19.
29. İslamov, İ.C. Respublikaba elektromaqnit təhlükəsizliyinin təmininin konseptual prinsiplərinin bəzi məsələləri // Beynəlxalq elmi-praktiki konfransın materialları, – Lənkəran: – 25 mart, – 2006, – s. 21-22.
30. Исламов, И.Дж. К определению парадоксов при решении уравнений Максевелла // AzTU-nun professor-müəllim heyətinin ETK məruzə materialları, – Bakı: – 2006, – 1-ci hissə, – s. 111-114.

31. İslamov, İ.C. Qeyri-müntəzəm divarlı düzbucaqlı dalğaötürənin səthi impedansının riyazi modeli // – Bakı: AzTU-nun elmi əsərləri, – 2007. №1, – s. 67-68.
32. İslamov, İ.C. İfrat yüksək tezlikli qurğuların optimal sintezi // – Bakı: Elm, – 2007, – 226 s.
33. Исламов, И.Дж. Определения постоянных распространения и построения структуры полей электромагнитных волн в круглом волноведущем устройстве телекоммуникации // 13th Azerbaijan International Exhibition and Conference "Telecommunications and Information Technologies", – Baku: – 2007, – pp. 147-150.
34. İslamov, İ.C. İfrat yüksək tezlik diapazonlu qurğuların hazırlanmasında buraxıla bilən xətaların optimallaşdırılması // Azərbaycanda televiziyanın 50, radionun 80 illiyinə həsr edilmiş "Radiotexnika, televiziya və rabitənin müasir problemləri" mövzusunda beynəlxalq elmi-texniki konfransın materialları, – Bakı: – 4-6 iyun, – 2007, – s. 85-90.
35. Исламов, И.Дж. Разработка математических моделей постоянных распространения электромагнитных волн в круглом волноводе при цифровом вещании // Материалы РНТК «Инновационные технологии в образовании и науке», посвященной 60-летному юбилею АзТУ, – Баку: – 2010, – с. 212-215.
36. İsmibəyli, E.Q. Müasir riyazi üsullar vasitəsilə ifrat yüksək tezlikli radiotexniki qurğuların analizi və optimal sintezi / E.Q.İsmibəyli, İ.C.İslamov, Y.Q.Qaziyev, M.M.Quliyev, R.Ş.Abdullayev, – Bakı: Dövlət büdcəli ETİ, – 2006-2010, №0106Az100956, – inv. №0211Az0059, – 25 s.
37. Исламов, И.Дж., Расулов, Р.Дж. Электродинамическое моделирование электромагнитных полей в круглом волноводе // – Москва: Электросвязь, – 2010. №10, – с. 16-18.
38. Исламов, И.Дж., Расулов, Р.Дж. Разработка математических моделей постоянных распространения электромагнитных волн в круглом волноводе при цифровом вещании // – Одесса: Цифровые технологии, 2010. №7, – с. 56-60.

39. Исламов, И.Дж., Джафарзаде, М.Б. Экспериментальное исследование электромагнитного поля в прямоугольном волноводе // “Müasir İKT inkişaf perspektivləri” beynəlxalq elmi-texniki konfransının materialları, – Bakı: – 22-24 sentyabr, – 2011, – s. 162-172.
40. Məmmədov, H.Ə., İslamov, İ.C. Qeyri-müntəzəm divarlı düzbucaqlı dalğaötürəndə səthi impedasın riyazi modeli // “Müasir İKT inkişaf perspektivləri” beynəlxalq ET konfransının materialları, – Bakı: – 22-24 sentyabr, – 2011, – s. 102-107.
41. Исламов, И.Дж., Джафарзаде, М.Б. Моделирование анизотропного прямоугольного волновода, частично внедренного в анизотропную подложку // – Баку: Известия НАН Азербайджана, Сер. физ. мат. и техн. наук., – 2011. №5, – т. 31, – с. 173-178.
42. Məmmədov, H.Ə. Elektrodinamika və radioekologiya. Monoqrafiya. / H.Ə.Məmmədov, E.Q.İsmibəyli, İ.C.İslamov – Bakı: Elm nəşriyyatı, – 2011. – 609 s.
43. Islamov, I.J., Asgarov, A.S. Calculation of the Electromagnetic Field of the Microwave Devices With Use of Method FDTD and Integral Kirchhoff // Application of Information and Communication Technologies-AICT2013, Baku: – 2013, – pp. 223-226.
44. İslamov, İ.C., Abdullayev, R.Ş., Camalova, J.S. Telekommunikasiya sistemlərinin ifrat yüksək tezlikli qurğularının hazırlanmasında buraxıla bilən xətaların optimallaşdırılması // “İnformasiya və kommunikasiya texnologiyalarının müasir vəziyyəti və inkişaf perspektivləri” beynəlxalq ET konfransın materialları, – Bakı: – 27-28 oktyabr, – 2014, – s. 63-69.
45. Исламов, И.Дж., Аскеров, А.С., Джамалова, Ж.С. Экспериментальное исследование параметров тракта сверхвысокочастотных устройств // – Bakı: AzTU-nun elmi əsərləri, – 2014. № 4, – cild 1, – s. 25-32.
46. Исламов, И.Дж. Моделирование электромагнитных полей СВЧ устройств телекоммуникаций / И.Дж.Исламов. – Germany: LAP Lambert Academic Publishing, – 2014, – 239 с.

47. Ismibayli, E.G., Islamov, I.J., Gaziyev, Y.G. Modeling of Anisotropic Rectangular Waveguide Partially Embedded in an Anisotropic Substrate // – Turkey: Journal of Multidisciplinary Engineering Science and Technology, – 2015. Vol. 2, – Issue 2, – pp. 153-157.
48. Исламов, И.Дж., Аскеров, А.С. Электродинамическое моделирование пространственной структуры электромагнитных полей в круглом волноводе сверхвысокочастотного диапазона телекоммуникаций // – Bakı: AzTU-nun elmi əsərləri, – 2015. № 1, – cild 1, – c. 21-29.
49. İsmibəyli, E.Q., İslamov, İ.C. İfrat yüksək tezlikli (İYT) radiotexniki element və qurğuların ədədi üsullar əsasında müasir kompüterlərdə "Matlab" proqramının tətbiqilə modelləşdirilməsi, analizi və optimal sintezi üçün alqoritmlərin işlənib hazırlanması // – Bakı: Dövlət büdcəli elmi-tədqiqat işi. – Dövlət qeydiyyat № 0111Az1075, – invertar № 0315Az0393, – 2015, – 44 s.
50. İslamov, İ.C. İfrat yüksək tezlikli düzbucaqlı dalğaötürəndən dairəvi dalğaötürənə keçid qurğusunda elektromaqnit sahəsinin modelləşdirilməsi // – Bakı: AzTU-nun elmi əsərləri, – 2015. №4, – cild 1, – s. 25-32.
51. Ismibayli, E.G., Islamov, I.J., Gaziyev, Y.G. Calculation Of The Electromagnetic Field Of The Microwave Of Devices With Use Of Method FDTD And Integral Kirchhoff // – Bhopal: International Journal of Engineering Innovation and Research, – 2016. Vol. 5, – Issue 1, – pp. 103-106.
52. Ismibayli, E.G., Islamov, I.J., Gaziyev, Y.G. Modeling Of Electromagnetic Fields Of Microwave Devices On The Basis Of Matlab Program // – Lucknow: International Journal of Innovative Science Engineering and Technology, – 2016. Vol. 3, – Issue 2, – pp. 61-63.
53. Ismibayli, E.G., Islamov, I.J., Gaziyev, Y.G. An Optimal Control Of An Electromagnetic Field In High-Powered Microwave Device // – Ranchi: International Journal of Trend In Research and Development, – 2016. Vol. 3(1), – pp. 246-249.

54. Исламов, И.Дж., Халилов, А.И. Электродинамические методы расчета сверхвысокочастотных устройств телекоммуникаций // – Екатеринбург: Национальная Ассоциация Ученых (НАУ), – 2016. №1, (17), – ч. 1, – с. 47-49.
55. İslamov, İ.C. Verici və qəbuledici antenalar arasında düzbucaqlı dalğaötürəndən rupora keçid qurğusundan şüalanan elektromaqnit sahəsinin intensivliyinin təcrübi təyini // – Bakı: AMEA-nın xəbərləri, fizika-texnika və riyaziyyat elmləri seriyası, – 2016. №2, – cild 36, – s. 128-132.
56. İslamov, İ.C. İfrat yüksək tezlikli düzbucaqli dalğaötürəndən rupora keçid qurğusunun xarakteristikalarının eksperimental tədqiqi // – Bakı: AzTU-nun elmi əsərləri, – 2016. №1, – cild 1, – s. 12-17.
57. Исламов, И.Дж., Абдуллаев,
58. Ismibayli, E.G., Islamov, I.J., Abdullayev, R.Sh. Numerical Simulation and Experimental Investigation of Rectangular Waveguide Electrical Field Taking Into Account Nonlinear Means // – New York: American Journal of Engineering Research, – 2016. Vol. 5, – Issue 4, – pp. 38-45.
59. Ismibayli, E.G., Islamov, I.J., Gaziyev, Y.G. New Approach to Definition of Potential of the Electric Field Created by Set Distribution in Space of Electric Charges // – Bangalore: International Journal of Engineering Research and Management, – 2016. Vol. 3, – Issue 3, – pp. 145-149.
60. Ismibayli, E.G., Islamov, I.J., Gaziyev, Y.G. Simulation of electromagnetic field from microwave rectangular waveguide to circular in transition devices // – Patna: International Journal of Engineering Sciences and Research Technology, – 2016. Vol. 5, – Issue 3, – pp. 695-704.
61. Islamov, I.J., Ahmadova, S.R. Experimental study of characteristics of microwave devices transition from rectangular waveguide to the megaphone // – Patna: International Journal

of Engineering Sciences and Research Technology, – 2016. Vol. 5, – Issue 5, – pp. 367-372.
62. Исмибейли, Э.Г., Исламов, И.Дж., Газиев, Ю.Г., Халилов, А.И. Методы оптимального управления электромагнитного поля в СВЧ устройствах телекоммуникаций // "İnformasiya və kommunikasiya texnologiyalarının müasir vəziyyəti və inkişaf perspektivləri" beynəlxalq elmi-texniki konfransının materialları, Bakı: – 23-25 noyabr, – 2016, – s. 22-31.
63. Исламов, И.Дж. Математическое моделирование электромагнитного поля СВЧ полого круглого волновода передачи информации // – Bakı: AzTU-nun elmi əsərləri, – 2016. №4, – cild 1, – s. 11-26.
64. Исламов, И.Дж. Обобщенные математические модели электромагнитного поля СВЧ прямоугольного волновода телекоммуникаций // – Bakı: AzTU-nun elmi əsərləri, – 2017. №1, – s. 17-36.
65. Исламов, И.Дж. Моделирование электромагнитного поля сверхвысокочастотного прямоугольного волновода телекоммуникаций методом конечных элементов // – Bakı: AzTU-nun elmi əsərləri, – 2017. №2, – s. 21-33.
66. Исламов, И.Дж. Обобщенные математические модели электромагнитного поля СВЧ двухпроводной линий передачи информации // – Bakı: AzTU-nun elmi əsərləri, – 2017. №3, – s. 11-21.
67. Исламов, И.Дж. Расчет основных параметров СВЧ прямоугольного волновода при нелинейной трактовке // – Bakı: AzTU-nun elmi əsərləri, – 2017. №4, – s. 31-43.
68. Islamov, I.J. Experimental study of characteristics of microwave devices transition from rectangular waveguide to the megaphone // Proceedings of the International Symposium of Mechanism and Machine Science, – Baku: – 11-14 September, – 2017, – pp. 187-191.
69. Исмибейли, Э.Г., Исламов, И.Дж. Математическое моделирование электромагнитного поля СВЧ полого круглого волновода передачи информации // Материалы XXII Международной научно-технической конференции «Совре-

менные средства связи», – Минск: – 19-20 октября, – 2017, – с. 93-95.
70. İslamov, İ.C. Qeyri-xətti mühitli ifrat yüksək tezlikli dalğaötürənlərin optimal sintezi. “Təhsil-tədqiqat-istehsalat mexanizminin qurulması” mövzusunda Respublika Elmi-texniki konfransının materialları, – Bakı: – 4-5 aprel, – 2018, – s. 52-55.
71. İslamov, İ.C. İfrat yüksək tezlik diapazonlu dairəvi dalğaötürən telekommunikasiya qurğusunun modelləşdirilməsi // – Bakı: Azərbaycan Dövlət Dəniz Akademiyasının elmi əsərləri, – 2018, – s. 56-62.
72. Исмибейли, Э.Г., Исламов, И.Дж. Моделирование электромагнитного поля прямоугольного волновода передачи энергии // Труды международной научно-технической конференции «Актуальные вопросы энергоснабжения как требование безопасности жизнедеятельности», – Киев: – 7-8 июнь, – 2018, – с. 47-53.
73. Исламов, И.Дж. Математические модели прямоугольного волновода передачи СВЧ информации // Материалы международной конференции «Актуальные проблемы математики и механики», – Баку: – 17-18 май, – 2018, – с. 156-157.
74. Islamov, I.J., Ismibayli, E.G. New Approach to Definition of Potential of the Electric Field Created by Set Distribution in Space of Electric Charges // World Congress of the International Federation of Automatic Control (IFAC), – Baku: – 13-15 September, – 2018, – pp. 204-209.
75. Islamov, I.J., Ismibayli, E.G. Experimental Study of Characteristics of Microwave Devices Transition From Rectangular Waveguide to the Megaphone // World Congress of the International Federation of Automatic Control (IFAC), – Baku: – 13-15 September, – 2018, – pp. 225-230.
76. Исмибейли, Э.Г., Исламов, И.Дж. Электродинамическое моделирование электромагнитного поля прямоугольного волновода передачи информации // Материалы XXIII Международной научно-технической конференции «Сов-

ременные средства связи», – Минск: – 18-19 октября, – 2018, – с. 65-67.
77. İslamov, İ.C. Qeyri-xətti mühitdə ifrat yüksək tezlik diapazonlu düzbucaqlı dalğaötürən qurğusunun modelləşdirilməsi// "Telekommunikasiyada innovativ texnologiyalar" mövzusunda beynəlxalq elmi-texniki konfransın materialları, – Bakı: – 4-6 dekabr, – 2019, – s. 54-58.
78. Islamov, I.J. Mathematical modeling of the electromagnetic field of a circular information transfer waveguide // 1st International Scientific-Practical Conference on "Universities of Azerbaijan and Turkey: Education, Science, Technology", – Baku: – 18-20 December, – 2019. Vol. 3, – pp. 485-492.
79. Islamov, I.J. Modeling of the Electromagnetic Feld of a Rectangular Waveguide With Side Holes / I.J.Islamov, E.G.Ismibayli, Y.G.Gaziyev, S.R.Ahmadova, R.Sh.Abdullayev // Progress In Electromagnetics Research, – Massachusetts, USA: – 2019. Vol. 81, – pp. 127-132.
80. Islamov, I.J. Calculation of the Electromagnetic Field of a Rectangular Waveguide with Chiral Medium / I.J.Islamov, E.G.Ismibayli, M.H.Hasanov, Y.G.Gaziyev, S.R.Ahmadova, R.Sh.Abdullayev // Progress In Electromagnetics Research, – Massachusetts, USA: – 2019. Vol. 84, – pp. 97-114.
81. Hasanov, M.H. About a principle of the prevention of attacks in optical networks / M.H.Hasanov, I.J.Islamov, M.R.Maharramzadeh, A.G.Imanguliyev, N.J.Zamanova, Sh.F.Gojayeva// – T-Comm, Moskow: – 2019. Vol. 13, – pp. 70-75.
82. Islamov, I.J., Hasanov, M.H. Simulation of a waveguide with a nonlinear medium // The 13th IEEE International Conference on Application of Information and Communication Technologies AICT2019, Baku: – 23-25 October, – 2019, – pp. 89-94.
83. Исламов, И.Дж., Исмибейли, Э.Г. Моделирование круглого диэлектрического волновода передачи электромагнитной энергии // Труды международной научно-технической конференции «Актуальные вопросы энергоснаб-

жения как требование безопасности жизнедеятельности», Киев: – 4-5 июнь, – 2019, – с. 121-127.
84. Islamov, I.J. Numerical methods of modeling a rectangular waveguide for transmitting electromagnetic energy // Thirteen International Conference on Thermal Engineering: Theory and Applications, Canada: – 12-14 June, – 2020, – pp. 176-182.
85. Islamov, I.J. Numerical simulation of a system of rectangular and circular waveguides for transmitting electromagnetic energy // Thirteen International Conference on Thermal Engineering: Theory and Applications, Canada: – 12-14 June, – 2020, – pp. 183-190.
86. Islamov, I.J., Shukurov, N.M., Abdullayev, R.Sh., Hashimov, Kh. Kh., Khalilov, A.I. Diffraction of Electromagnetic Waves of Rectangular Waveguides With a Longitudinal // XXIII International Conference WECONF-2020, “2020 wave electronics and its application in information and telecommunication systems”, St. Petersburg: – 01-05 June, – 2020, – pp. 1-7.
87. Khalilov, A.I., Islamov, I.J., Hunbataliyev, E.Z., Shukurov, N.M., Abdullayev, R.Sh. Modelıng microwave signals transmitted through a rectangular waveguide. XXIII International Conference WECONF-2020, “2020 wave electronics and its application in information and telecommunication systems”, St. Petersburg: – 01-05 June, – 2020, – pp. 8-15.
88. Islamov, I.J., Mityuk, L.A. Mathematical modeling of electromagnetic waves of a rectangular waveguide transmiting energy. III International Scientific and Practical Conference “Energy saving and occupation safety: challenges and opportunities”, Kiev: – 2-3 June, – 2020, – c. 104-111.
89. İfrat yüksək tezlikli elektron və kvant cihazları: ali məktəblər üçün dərslik / E.Q.İsmibəyli, İ.C.İslamov, Y.Q.Qaziyev, S.Əhmədova, E.Z.Hünbətəliyev – Bakı: Elm, – 2020, – 314 s.
90. Исламов, И.Дж., Халилов, А.И. Моделирование электромагнитного поля сверхвысокочастотного прямоугольного волновода телекоммуникаций методом конечных элемен-

тов // – Минск: Научный журнал “Проблемы инфокоммуникаций”, – 2020. № 1 (11), – с. 75-86.
91. Islamov, I.J. Numerical simulation of characteristics of propagation of symmetric waves in microwave circular shielded waveguide with radially inhomogeneous dielectric filling // Azərbaycan Texniki Universitetinin 70 illik yubileyinə həsr olunmuş “Dördüncü sənaye inqilabının texnoloji perspektivləri: sənaye interneti, kiberfiziki sistemləri və intellektual texnologiyalar” mövzusunda respublika elmi-texniki konfransının matereialları, – Bakı: – 26-28 noyabr, – 2020, – s. 113-120.
92. Islamov, I.J., Hunbataliyev, E.Z., Zulfugarli, A.E. Modeling of microwave waveguide system with complex structure in nonlinear // International Conference “Engineering management of communication and technology”, – Vienna: – 20-22 October, – 2021.
93. Khalilov, A.I., Islamov, I.J., Hunbataliyev, E.Z., Maharramov, V.A. Numerical simulation of a circular dielectric microwave waveguide with a complex cross-section // International Conference “Engineering management of communication and technology”, – Vienna: – 20-22 October, – 2021.
94. Islamov, I.J., Khalilov, A.I. Modeling a rectangular microwave waveguide used in digital television systems // XXVI International Scientific and Technical Conference “Modern Communication Means”, – Minsk: – 21-22 October, – 2021.
95. Islamov, I.J. Design of Radio-Electronic Means Taking into Account Electromagnetic / I.J.Islamov, E.Z.Hunbataliyev, M.F.Binnatov, A.E.Zulfugarli // Thermal and Mechanical Characteristics, EasyChair Preprint, – London: – 2021. № 4872, – 15 p.
96. Islamov, I.J., Hunbataliyev, E.Z., Zulfugarli, A.E. Numerical Simulation of Characteristics of Propagation of Symmetric Waves in Microwave Circular Shielded Waveguide With a Radially Inhomogeneous Dielectric Filling // – Cambridge

University Press: International Journal of Microwave and Wireless Technologies, – 2021. Vol. 9, – pp. 1-7.

97. Islamov, I.J., Hunbataliyev, E.Z., Abdullayev, R.Sh., Shukurov, N.M., Hashimov, Kh. Kh. Modelling of a Microwave Rectangular Waveguide With a Dielectric Layer and Longitudinal Slots // International Symposium for Production Research 2021, Antalya: – 07-09 October, – 2021.
98. Islamov, I.J., Hasanov, M.H., Hunbataliyev, E.Z., Zulfugarli, A.Z. Relativistic calculations on the transmitting electromagnetic energy along a microwave rectangular waveguide // International Symposium for Production Research 2021, Antalya: – 07-09 October, – 2021.
99. Islamov, I.J., Hasanov, M.H., Abbasov, M.H. Simulation of Electrodynamic Processes in a Cylindrical-Rectangular Microwave Waveguide Systems Transmitting Information // 11th International Conference on Theory and Application of Soft Computing, Computing with Words, Perception and Artificial Intelligence, ICSCCW – 2021, Antalya: – 23-24 August, – 2021.
100. Islamov, I.J., Huseynli, I.G., Abdullayev, R.Sh. Modeling of a Resonator in a Rectangular Waveguide for Transmitting Electromagnetic Energy // II International Scientific Forum on Computer and Energy Sciences, WFCES II – 2021, Almaty: – 11-12 November, – 2021.
101. Islamov, I.J., Nuriyev, M.N. Simulation of a Circular Waveguide with a Complex Structure for Transmission of Microwave Signals // II International Scientific Forum on Computer and Energy Sciences, WFCES II – 2021, Almaty: – 11-12 November, – 2021.

Personal participation of the author in scientific works published with co-authors:

- [1, 2, 4-7, 9-11, 13, 15, 19-22, 25, 26, 28-35, 46, 50, 55, 56, 63-68, 70, 71, 73, 77, 78, 84, 85, 91] - works were performed independently by the author;

- [3, 8, 12, 14, 16-18, 23, 24, 27, 36-45, 47-49, 51-54, 57-62, 69, 72, 74-76, 79-83, 86-90, 92-101] - new mathematical models for the electromagnetic field of rectangular and circular waveguides from microwave radioengineering and telecommunication devices, taking into account the nonlinearity of the environment, the types of waves and algorithms developed for the solution of these models, the basic parameters of rectangular and circular waveguides, algorithms developed for the optimal synthesis of microwave rectangular and circular waveguides were implemented by the author.

The defense will be held on 05 november 2021 at 11^{00} at the meeting of the Dissertation council ED 2.41 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Azerbaijan Technical University.

Address: H.Javid ave 25, Baku, Azerbaijan, AZ 1073, Azerbaijan Technical University.

The dissertation is available in the library of the Azerbaijan Technical University.

Electronic versions of dissertation and its abstract are available on the official website of the Azerbaijan Technical University.

Abstract was sent to the required addresses on 30.09.2021.

Signed for print: 27.09.2021
Paper format: A5
Volume: 76000
Number of hard copies: 20