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Investigation of electrodynamic properties of mushroom metamaterials and design of microwave frequency-selective devises based on them

Dissertation summary

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Relevance

At the present stage of development of radio electronics and microwave technology, the requirements for microwave frequency-selective devices (MFSDs) have significantly increased. As a response to these challenges, metamaterials have been increasingly used to improve the performance of frequency-selective devices or to achieve properties that are unattainable in classical electrodynamic structures. One of the types of metamaterials is the so-called mushroom-shaped metamaterial. It is a planar structure that can be described as a variant of realization of a high-impedance surface. Its main advantages are simplicity of fabrication, possibility to create small-sized devices for various purposes on its basis, as well as wide possibilities to adjust its parameters both at the stage of development and design, and in real time during operation.

State of the matter

One of the important trends in the development of modern microwave frequency-selective devices is the introduction of structures with metamaterials in order to achieve better electrical and mass-size characteristics.

Due to the lack of generally accepted methods of accurate calculation of parameters and synthesis of MFSDs on planar mushroom-shaped metamaterials, developers of such devices have to resort to various approximate analytical methods of assessing the characteristics of the metamaterial, and further verify these estimates by computer modeling. Nowadays, due to wide application of numerical modeling methods and increase of computing power, planar mushroom-shaped metamaterials have found wide application in electrodynamics and microwave engineering [1, 2, 3, 4].

Due to rapidly increasing accuracy requirements as well as limitations inherent in measurements using resonant sections of classical transmission lines, sensing elements based on metamaterials have become widespread. Metamaterials can demonstrate strong localization and concentration of electromagnetic fields, which increases sensitivity and allows to register even small changes of controlled quantities, small concentrations of substances or small-sized defects in the investigated media [5, 6].

The resonance properties of planar mushroom-shaped metamaterials directly depend on the properties of their constituent cells. Therefore, there is a possibility of flexible tuning of frequency-selective properties of devices with planar mushroom-shaped metamaterial by making various modifications in the structure of the metamaterial, for example, combining different types or sizes of cells to expand or shift the operating bands [7, 8].

Planar mushroom-shaped metamaterials are widely used in antenna technology as grounding layers and decoupling elements. The advantage of metasurfaces over conventional grounds are more effective cutoff of parasitic back radiation and reduction of associated losses, suppression of surface waves and the possibility of reducing the size of the antenna by placing the transmitter directly on the metasurface without the danger of shorting it out [9].

Metamaterials used as inserts in waveguide paths exhibit filter properties and make it possible to obtain both band-pass and band-stop filters, and the operating bandwidth of the latter can be below the cutoff frequency of the waveguide itself, which means an extension of its operating range [10].

Due to simplicity and cheapness of manufacturing, frequency-selective surfaces on mushroom-shaped metamaterials have become an accessible and widespread solution in the design of MFSDs of various purposes.

Purpose and objectives of the dissertation research

The aim of this dissertation is to investigate the physical, structural and technological features of mushroom-shaped metamaterials and to develop on their basis small-sized microwave frequency-selective devices for various functional purposes with improved electrodynamic parameters and characteristics.

To achieve this goal, it is necessary to solve the following problems:

- Analysis of known physical features, design methods, structural and technological solutions and applications of mushroom-shaped metamaterials, their advantages, disadvantages and trends of further development;

- analysis of analytical and numerical methods, as well as software tools for computer simulation of mushroom metamaterials;
- study of the influence of geometric dimensions of cells of mushroom-shaped metamaterials on equivalent parameters, dispersion and phase characteristics of frequency-selective surfaces on mushroom-shaped metamaterials;
- computer modeling of dispersion characteristics and S-parameters of electrodynamic structures and devices on mushroom-shaped metamaterials;
- experimental study of mockups of microwave frequency-selective devices based on a planar mushroom-shaped metamaterial and comparison of the obtained characteristics with the results of analytical calculations and computer simulation.

Provisions for the defense

The following new provisions obtained in the work are presented for the defense:

1. Approximate analytical methods of calculation based on the dependences between the geometric dimensions of the elementary cells of the metamaterial, the dielectric permittivity of the substrate, and its amplitude-frequency characteristics are the most effective for the theoretical study of the dispersion properties of electrodynamic structures based on mushroom-shaped metamaterials and devices based on them.
2. The phase of an electromagnetic wave reflected from a conformal frequency-selective surface on a metamaterial can be calculated using a geometric method based on the Snell’s law and elementary geometry. Due to the curvature of the frequency-selective surface, the incident electromagnetic wave travels an additional path, which leads to an increase in the phase shift of the reflected wave by a value that depends on the radius of curvature of the surface.

3. A section of rectangular waveguide, when one of its wide walls is made in the form of a mushroom-shaped metamaterial, provides resonance properties. The obtained rejection band can be expanded by 3.5 times by selecting the value of the relative permittivity of the substrate material and the geometric dimensions of the elementary cells of the metamaterial;
4. The use of mushroom-shaped elementary cells of two multiples of geometric dimensions (modulations) in the structure of the wide magnetic wall of the resonant section of the rectangular waveguide allows to obtain two rejection bands, the width of which can be adjusted by applying a layer of ferromagnetic on the surface of the elementary cells of the metamaterial.

Research Methodology

The research was carried out with the help of mathematical models of electrodynamics and electromagnetic field theory; theory of electric circuits and signals; numerical methods and computer modeling; fabricated experimental models and devices.

Reliability of scientific provisions, conclusions and results

Reliability of scientific statements, conclusions and results is confirmed by comparative analysis of analytical and numerical calculations, computer modeling and experimental data, consistency of a number of obtained results with the conclusions and results published by other authors in domestic and foreign publications.

Approbation of the work

The main theoretical and practical results of the thesis were presented and discussed at the following conferences:

1. International scientific and technical conference «Actual problems of electronic instrumentation», «Investigation of Sensing Element on Planar Mushroom Metamaterial» (in Russian), Saratov, September 22-23, 2016.

2. International scientific and technical conference «Actual problems of electronic instrumentation», «Waveguide Structures with Magnetic Walls on the Basis of the Mushroom-shaped Metamaterials», Saratov, September 24-25, 2020.
3. Interuniversity scientific and technical conference of students, graduate students and young specialists named after E. V. Armensky, «Investigation of Decoupling Filter Performance on a Metamaterial» (in Russian), Moscow, 17-29 February, 2016.
4. Interuniversity scientific and technical conference of students, graduate students and young specialists named after E. V. Armensky, « Investigation of Sensor Operation Modes on a Planar Mushroom-shaped Metamaterial» (in Russian), Moscow, February 17th – May 1st, 2017.
5. Interuniversity scientific and technical conference of students, graduate students and young specialists named after E. V. Armensky, « Modeling of a Sensor on a Mushroom-shaped Metamaterial with a Ferrite Layer» (in Russian), Moscow, February 19th – May 1st, 2018.
6. International Industry Scientific and Technical Conference «Information Society Technologies», «Investigation of small-size decoupling filter on metamaterial» (in Russian), March 16-17, Moscow, 2016.
7. International Industry Scientific and Technical Conference «Information Society Technologies», «Investigation of microwave sensor on mushroom-shaped metamaterial for measuring physical quantities and process parameters» (in Russian), March 15-16, 2017.
8. 14th European Conference on Antennas and Propagation (EuCAP-2020), «Computer Simulations of Multiband Waveguide Filter on Modulated Metasurface», Copenhagen, March 15-20, 2020.
9. Eighteenth International Vacuum Electronics Conference (IVEC-2017), «Investigation of a rectangular waveguide with a magnetic wall made of mushroom-shaped metamaterial», London, April 24-26, 2017.

10. Eighteenth International Vacuum Electronics Conference (IVEC-2017), «Investigation of microwave sensor on the planar mushroom-shaped metamaterial», London, April 24-26, 2017.
11. International Conference on Computer Simulation in Physics and beyond (CSP 2020), «Investigation of Filtering and Sensing Properties of Complementary Metamaterial Resonant Cells by Computer Simulation», Moscow, October 12-16, 2020.
12. 2018 12th International Congress on Artificial Materials for Novel Wave Phenomena (METAMATERIALS), «Metamaterial-based Sensor for Measurements of physical Quantities and Parameters of technological Processes», Espoo, August 27th – September 1st, 2018.
13. 2019 Systems of Signal Synchronization, Generating and Processing in Telecommunications SYNCHROINFO-2019, «Millimeter-wave metamaterial-based sensor for inhomogenity detection and parameter control of technological substances», Yaroslavl, July 1-3, 2019.
14. 2020 Systems of Signal Synchronization, Generating and Processing in Telecommunications SYNCHROINFO-2020, «Computer Model of a Frequency-Selective Surface on Mushroom-Shaped Metamaterial», Svetlogorsk, July 1-3, 2020.
15. 2022 Systems of Signal Synchronization, Generating and Processing in Telecommunications SYNCHROINFO-2022, «Simulation of a Frequency Selective Surface with Fractal Jerusalem Cross Unit Cells», Arkhangelsk, June 29th – July 1st, 2022.

Structure of the dissertation

The dissertation consists of an introduction, 4 chapters, a conclusion, a bibliography and two appendixes. The total volume of the thesis is 168 pages, including 60 figures.

In the first chapter of the thesis, the physical principles on which the operation of metamaterials is based are discussed, and a review of publications devoted to their development and application in microwave engineering is given. In particular, it is shown that absorbing structures on metamaterials exhibit absorption levels in excess of 95% in certain frequency ranges.

Moreover, implementation of metamaterials in antenna technology allows to increase antenna gain, directivity and reduce crosstalk by decoupling elements of antenna systems - all this while reducing or at least not increasing the overall dimensions of antennas.

The application of metamaterials as elements of sensors and sensors, including those designed to work with biological samples, has been studied as well. The review of publications has shown that the use of metamaterials in the design of such devices is a promising way to improve their characteristics, in particular, sensitivity. It is also revealed that it is possible to create promising devices for non-invasive diagnostics of various neoplasms in human tissues on the basis of frequency selective surfaces on metamaterials. The possibility of using frequency-selective surfaces on metamaterials to manipulate the properties of electromagnetic waves incident on them, in particular, to change their amplitude, phase, and polarization, has been studied separately.

In the second chapter, two analytical methods are presented to calculate the phase and dispersion properties of frequency-selective surfaces on a mushroom-shaped metamaterial. The analytical method for calculating dispersion properties allows us to determine the retardation factor of frequency-selective surfaces on a mushroom-shaped metamaterial and to evaluate the influence of the dielectric permittivity of the substrate. The method is based on the dependence of the dispersion properties of the mushroom-shaped metamaterial on the geometric parameters of its unit cells. The geometric method of calculating the phase shift in the reflection of an electromagnetic wave from a conformal metasurface allows us to calculate the additional phase run-up arising due to bending and to estimate the influence of the surface curvature radius on its value.

In the third chapter, a review of modern means of computer modeling of electrodynamic structures on metamaterials is made and a conclusion is made about the expediency of using the CST Studio Suite software and its module Microwave Studio for the numerical study of the developed microwave devices on a mushroom-shaped metamaterial.

The fourth chapter presents the results of research and development of MFSDs on mushroom-shaped metamaterial, namely: resonant waveguide sections with magnetic walls containing unit cells of one or two sizes, a sensing element on a mushroom-shaped metasurface, a waveguide matched load on a mushroom-shaped metamaterial. The experimental results on the developed sensing element are also given.

Personal contribution of the applicant

The personal contribution of the applicant consists in direct participation in the formulation of the research problems and their solutions, development of computer models of the devices presented in the thesis work, carrying out their numerical calculation and analysis of the obtained results. Also, the author personally made mockups of MFSDs on the mushroom-shaped metamaterial and conducted their experimental study. With the participation of the author prepared the main publications on the work performed.

Practical significance of the work

The main results of the thesis were obtained during the initiative work in the MIEM HSE with the participation of the applicant, as well as the implementation of three two-year grants of the Scientific Foundation of the HSE in the SRG "Electrodynamics of retarding systems":

1. Grant 17-05-0009, 2017-2018.
2. Grant 19-04-005, 2019-2020.
3. Grant 21-04-010, 2021-2022.

In the process of working on the thesis research, the following certificates of intellectual property were obtained:

1. Kukharenko A. S. S. Sensitive element on a metamaterial / A. S. Kukharenko, A. A. Elizarov, A. A. Skuridin, M. I. Zakirova / RF patent for a useful model № 170145. BI NO. 11, 2017.
2. Elizarov A. A., Malinova O. E., Sidorova T. V., Skuridin A. A. META. State Registration Certificate for Computer Software No. 2019613769 dated March 22, 2019

Also, the results of the dissertation research were used in project management:

1. MIEM student project #216, "Development of wearable antennas and emitters for the Internet of Things" (2020-2022).
2. Project "Development of wearable antennas and emitters for the Internet of Things" as part of the HSE project group competition (undergraduate and graduate students) (2020-2021).
3. MIEM Student Project #841, "Research on Modulated Frequency Selective Surfaces" (2021-2022).

Main results

The main result of the work is the solution of the actual problem, which consists in the study of the electrodynamic properties of structures on mushroom-shaped metamaterials and the development of new microwave small-sized frequency-selective devices based on them. The peculiarity of the work is its applied orientation, which allows one to use the obtained theoretical and experimental results to solve specific scientific and practical problems.

The main results of the work are as follows:

1. A review of the current state and trends in the development of microwave frequency-selective structures on metamaterials is performed. Their physical and structural features, limitations and opportunities to expand the functional purpose are considered. Numerical methods of calculation of electrodynamic structures on metamaterials and means of their computer modeling are also considered and analyzed. It is revealed that the use of structures on metamaterials in the

structures of microwave frequency-selective devices can improve their characteristics and reduce the overall dimensions.

2. Analytical methods for calculating the dispersion and phase characteristics of electrodynamic structures on a mushroom-shaped metamaterial are proposed:
   - An analytical method of calculation of resonance and dispersion characteristics of frequency-selective surface on a mushroom-shaped metamaterial based on dependence of frequency and dispersion characteristics on geometrical sizes and dielectric filling of both separate cells and the whole metasurface is proposed, by means of which it is revealed that the retardation coefficient of frequency-selective surface on a mushroom-shaped metamaterial decreases in 7 times at reduction of sizes of elementary cells in 3 times, and dispersion characteristic is reduced in 3 times. A direct dependence between the relative dielectric permittivity of the substrate material of the mushroom-shaped metamaterial and the retardation coefficient of the structure on it was also revealed, but the value of ε varying from 1 to 9.8 does not influence the character of the dispersion curves.
   - A geometric method for determining the phase shift in the in-phase reflection of electromagnetic waves from conformal elementary cells that form a frequency-selective metasurface is proposed. The method is based on the use of Snell's law and elementary geometry to determine the change in the angle of reflection of electromagnetic wave after bending of planar elementary cells. It is shown that due to the bending of the surface, the incident electromagnetic wave travels an additional path, which leads to an increase in the phase shift of the reflected wave.
3. A brief review of modern software tools for modeling electrodynamic structures is performed. It is concluded that full-wave modeling software is the most effective tool for the effective numerical analysis and refinement of the obtained approximate analytical models of electrodynamic structures.
4. The results of the analysis and theoretical research have found application in the design and experimental study of:

- resonant section of the waveguide with a magnetic wall on a mushroom-shaped metamaterial, which has a rejection bandwidth of at least 500 MHz and an attenuation of at least 15 dB, that can be expanded by 3.5 times compared to the air filling by selecting the substrate dielectric permittivity value;
- resonant waveguide section with a magnetic wall on a mushroom-shaped metamaterial, which has two rejection bands due to the use of the modulated structure of the mushroom-shaped metamaterial. The rejection is observed in the frequency ranges of 4.4-4.7 GHz and 5.3-6.5 GHz with metamaterial cell sizes of 8 × 8 mm and 4 × 4 mm. When a layer of ferrite is deposited on the surface of the cells, a shift of the rejection bands toward lower frequencies is observed, the magnitude of which depends on the thickness of the sputtering and the value of its relative magnetic permeability;
- matched waveguide load with end wall on mushroom metamaterial with VSWR from 1.13 to 1.15 in the range of 14.8-16.5 GHz;
- sensing element on a mushroom-shaped metamaterial designed to control geometric dimensions, dielectric permittivity and inhomogeneities of technological media. Sensitivity of the device to changes in dielectric permittivity of the investigated sample is 250 MHz/u; to changes in thickness 210 MHz/mm. Experimental research of the enlarged model of the given sensitive element confirmed theoretical conclusions about the possibility of control of geometrical parameters of the investigated sample with its help. The error between the numerical and experimental results was not more than 4%.

List of published works on the topic of the dissertation

The author’s 12 publications are presented in peer-reviewed scientific journals included in the international citation systems Scopus and Web of Science:

1. Rano D., Yelizarov A. A., Skuridin A. A., Zakirova E. A. Geometric Method for Determining the Phase Shift in the Reflection of an Electromagnetic Wave from

a Conformal Meta-Surface of a Sensing Element // Meas. Tech. 2022. №65, pp. 273–278.

2. Yelizarov A. A., Skuridin A. A., Zakirova E. A. Simulation of Sensitive Element Found on Planar Mushroom-Shaped Metamaterial for Nondestructive Testing and Searching for Inhomogeneities in Technological Media // Meas. Tech. 2021. №63, pp. 828–833.
3. Skuridin A. Computer Simulation of Modulated Frequency Selective Surfaces on Mushroom-Shaped Metamaterials / Yelizarov (Elizarov) A. A., Nazarov I., Skuridin A., Zakirova E., Rano D. // Conf. Proceedings 2021 Systems of signals generating and processing in the field of on board communications. 2021. pp. 1-4.
4. Yelizarov A. A., Skuridin A. A., Nazarov I. V., Zakirova E. A. Simulation of a Frequency Selective Surface with Fractal Jerusalem Cross Unit Cells // Conf. Proceedings 2022 Systems of Signal Synchronization, Generating and Processing. 2022. pp. 4-4.
5. Yelizarov (Elizarov) A. A., Nazarov I., Skuridin A., Zakirova E. Waveguide Structures with Magnetic Walls on the Basis of the Mushroom-shaped Metamaterials / // Conf. Proceedings 2020 International Conference on Actual Problems of Electron Devices Engineering (APEDE). 2020, pp. 175-179.
6. Skuridin A., Yelizarov (Elizarov) A. A., Nazarov I., Zakirova E. Investigation of Filtering and Sensing Properties of Complementary Metamaterial Resonant Cells by Computer Simulation // Journal of Physics: Conference Series. 2021. No. 1740. Article 012023.
7. Yelizarov (Elizarov) A. A., Nazarov I., Skuridin A., Zakirova E. Computer Model of a Frequency-Selective Surface on Mushroom-Shaped Metamaterial // Conf. Proceedings 2020 Systems of Signal Synchronization, Generating and Processing in Telecommunications. 2020. pp. 1-4.
8. Yelizarov (Elizarov) A. A., Nazarov I., Skuridin A. Computer Simulations of Multiband Waveguide Filter on Modulated Metasurface // Conf. Proceedings 14th European Conference on Antennas and Propagation. 2020. pp. 1-4.

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10. Skuridin A. A., Yelizarov (Elizarov) A. A., Kukharenko A. S. Millimeter-Wave Metamaterial-Based Sensor for Inhomogeneity Detection and Parameter Control of Technological Substances // Conf. Proceedings 2019 Systems of Signal Synchronization, Generating and Processing in Telecommunications. 2019. pp. 1-4.
11. Yelizarov (Elizarov) A. A., Nazarov I., Skuridin A., Kukharenko A. S. Investigation of a rectangular waveguide with a magnetic wall made of mushroom-shaped metamaterial // Conf. Proceedings 18th International Vacuum Electronic Conference. 2017. pp. 1-3.
12. Yelizarov (Elizarov) A. A., Nazarov I., Kukharenko A. S., Skuridin A. A. Investigation of microwave sensor on the planar mushroom-shaped metamaterial // Conf. Proceedings 18th IEEE International Vacuum Electronic Conference. 2017. pp. 1-2.

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