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THz antenna arrays utilizing planar Schottky barrier diodes

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Introduction

Schottky barrier diode technology has been known to the scientific and engineering community since the late 1930s. [1; 2]. As requirements for the number and uniformity of diode elements in nonlinear frequency conversion devices in wireless communications, radar, and remote monitoring applications have grown, historically the first whisker design has given way to the planar design. Moreover, the continuous progress of terahertz (THz) technology [3] stimulates the introduction of new and development of existing technologies for both sources and receivers of radiation in this frequency range. At the moment, there are several basic technologies for heterodyne detection of THz radiation. Thus, a mixer based on the superconductor-insulator-superconductor (SIS) junction is extremely efficient at frequencies below 1.4 THz [4]. It is advisable to use a mixer based on the electron heating effect (HEB) in thin films of a superconductor in a resistive state at higher frequencies; in particular, it has no competitors in terms of the combination of sensitivity and speed in the range of 3–6 THz [5]. The lower bound of this frequency region is also the upper bound of the input operating bandwidth of the planar Schottky diode (PSD) mixer, which is limited to ∼3 THz [6]. Unlike SIS and HEB superconducting mixer technologies, Schottky diode technology is a semiconductor technology and primarily uses a GaAs layered structure, meaning there is no need for bulky and expensive cryogenic equipment to achieve acceptable receiver noise performance. The absence of the need to cool PSD to helium temperatures makes it very attractive for practical use. Although in recent years the technology of high-temperature HEB detectors, operating at liquid nitrogen temperatures of [7] and, therefore, less energy-consuming than receivers using liquid helium as a coolant, has been developing quite successfully, they are still continuing to develop. is not able to replace uncooled semiconductor devices of a similar class. The most important factor in the success of planar technology, in contrast to filamentary diode technology, is that the former allows precise control of the parameters of manufactured devices and easy integration of them into complex high-frequency circuits. However, despite its many advantages,

planar technology has certain disadvantages associated with the appearance of series resistance and shunt capacitance in the diode's own circuitry. Eddy currents induced in the layered structure of PSD also significantly affect its characteristics in the THz range [8]. The eddy current effect is present in devices with relatively thick mesas and depends on their geometry. From the point of view of the equivalent circuit of the PSD, this can be represented as a series-connected inductance, which in a certain way limits the band of input operating frequencies of the diode. However, by reducing the thickness of the mesa to a certain value comparable to the depth of the skin layer at the corresponding frequency, this negative effect can be mitigated [9]. Moreover, at submicron thicknesses, such manipulation can lead to a significant complication of diode structuring.

In this study, PSD with a mesa thickness of the order of one skin layer thickness are used. This is done in order to potentially mitigate the effect of eddy currents, as well as the skin and proximity effects of the PSD, the loss of which at radio frequency will be determined only by its a) parasitic parameters, including shunt capacitance, series inductance and resistance, and b) transport properties according to direct current. Multi-element coherent and incoherent receivers based on Schottky diodes in the terahertz range are in demand in modern ground-, balloon- and space-based radio astronomy systems, in agricultural systems for monitoring the hydration of crops, in multibeam wireless communication systems [10—13] and others applied tasks requiring the use of technologically advanced and energy-efficient terahertz radiation sensors.

Antenna arrays and metasurfaces that provide real-time routing of radio signals are designed to improve the robustness of wireless connections in next-generation communications networks. Today, society's needs for information processing capabilities are inevitably growing. This motivates active research in the field of next-generation communications [14]. The terahertz frequency band is considered useful for future sixth generation (6G) wireless communications networks. However, its use is accompanied by the need to deal with high propagation losses due to atmospheric

absorption, scattering from obstacles and dynamic blocking [A1]. Thus, 6G wireless systems must rely on THz transmitters and receivers with highly directional, reconfigurable beams. This, together with the use of intelligent reflective surfaces (IRS), is proposed as a promising solution to improve signal transmission at carrier frequencies above 100 GHz [15].

Generally speaking, an IRS consists of multiple periodic elements that provide effective wavefront control by varying phase, magnitude, and polarization as the beam is routed [16]. Recently, a large number of IRS designs have been proposed. These include devices with tuning mechanisms based on I) slow-acting liquid crystals and microelectromechanical systems, II) ultra-fast transistor and diode electronics [17].

Considering the IRS as part of a wireless THz channel, it is necessary to take into account the phase-dependent amplitude response of its unit cells, as well as the cross-coupling between them[18]. Optimization of beamforming can be performed either analytically, using the IRS generalized structure equivalent circuit model [19], or numerically, through electromagnetic (EM) modeling [20]. However, most recently published IRS models target operating frequencies well below 100 GHz, where discrete metal-oxide-semiconductor FETs and varactor or PIN diodes can be used for phase shifting [21—23]. This leads to many unconsidered aspects associated with the design and implementation of THz IRS in the form of a monolithic integrated circuit (IC). Moreover, existing IRS unit cell models are very indirectly related to semiconductor physics. They do not allow easy prediction of performance changes at different incident power levels due to the temperature-dependent transport properties of space charge regions in IRS unit cells [24; 25].

The use of Schottky diodes in the IRS unit cell provides a switching time of its states of less than a picosecond [26]. Taking into account the fundamental non-inertia of charge carriers, the performance of a Schottky diode is completely determined by the manufacturing technology [6] and the EM design of its IC [27]. Thus, the emergence of time-efficient and predictively reliable modeling methods is

extremely important for the further development of THz Schottky diode technology and integrated devices using them.

Thus, the **relevance** of this dissertation research is due to several main points: a) the need to increase the operating frequency band and signal readout speed of uncooled diode receivers in the terahertz range; b) the need to develop parameterized models and technological designs of reconfigurable terahertz antenna arrays with ultra-fast beamforming to ensure indirect connection in new generation communication channels; c) the need to identify practical requirements for reconfigurable terahertz antenna arrays for new generation communication channels supporting indirect connection.

It should also be noted that most of the research described in this dissertation was carried out as part of research work, including 3 projects at the National Research University Higher School of Economics, namely, «Dynamic Blockage and Micromobility Processes in 6G Communication Networks» (2022), «Study of the indoor propagation of terahertz waves for the development of averaged and three-dimensional cluster models of 6G communication channels» (2023), «Study of promising software, hardware and algorithmic solutions to combat radio signal blocking and the effect of subscriber micromobility in 6G networks» (2024), and 2 projects of the Russian Science Foundation at Moscow Pedagogical State University, namely, «Terahertz photonic integrated phased array antennas for creation of the new generation telecommunication» (2021–2024), «A mm-Wave intelligent reflective surface for next generation communication systems» (2022–2025).

The purpose of this research work is to study the issues of creating multi-element nonlinear devices for routing and receiving terahertz waves for 6th generation wireless communication systems.

To achieve the set purpose, the following **tasks** were solved:

1. Methods and auxiliary means for measuring the characteristics of antenna arrays designed for reflecting and detecting narrow terahertz beams have been

developed, namely, a method and set up for measuring the noise equivalent power of a Schottky barrier diode detector with readout of a signal using a microwave reflectometer, a method and set up for measurement radiation patterns of a reflector with diode switches in the terahertz range.

2. The features of the phenomenon of dynamic blocking of narrowly directed terahertz beams in direct and indirect visibility communications were experimentally studied to formulate requirements for the technical characteristics of antenna arrays as part of modern radio access networks with a carrier frequency in the range of 130–160 GHz. A set up and method have been created for measuring the dynamics of changes in the level of the received signal when the radio signal is blocked by the user's body in motion.

3. Models have been developed for the design of antenna arrays and their structural elements, namely, electromagnetic and hybrid parameterized models of a planar Schottky diode using the Lambert W_0-function, a compact microstrip dual-mode demultiplexer, a reconfigurable reflector cell with diode microswitches.

Antenna arrays using micro-sized Schottky barrier diodes, their models and designs, and basic radiophysical characteristics in the terahertz range were selected as the **Object** and **subject** of the study.

Scientific novely of the research.

1. A design of a planar Schottky diode with a Γ-shaped suspended anode bridge has been proposed, which makes it possible to reduce the influence of parasitic parameters of the diode at high-frequency current or to miniaturize the design while maintaining parasitic components at the original level.

2. The design of a matrix diode detector with a Schottky barrier with line-by-line frequency division of channels and a response readout system based on a microwave reflectometer has been developed that can increase the speed in

proportion to the number of lines of the detector with a twofold deterioration in sensitivity.

3. The values of the times of dynamic blocking and peak attenuation of the signal when it is blocked by a moving person, in connection with direct and indirect visibility, are determined for a point-to-point connection at a frequency of 156 GHz.

4. The values of the complex dielectric constant for sheet glass, plasterboard and aerated concrete, in the range of 132–162 GHz, were determined using the apparatus of the characteristic matrix of a layered medium, as well as models for the analysis of porous dielectrics. The latter considers the sample as a homogeneous medium with an effective dielectric constant and thus allows one to correctly estimate this value for aerated concrete.

5. A model of the unit cell of a reconfigurable terahertz antenna array with Schottky microcontacts has been developed, taking into account the impedance-voltage characteristics of the contact explicitly using the Lambert W_0-function, which makes it possible to improve the capabilities in the design of devices with discrete and continuous pattern formation in reflected beam.

Practical relevance. Multi-element coherent and incoherent terahertz receivers are in demand in modern instrumented radio astronomy complexes ground-based, aerostat and space-based, in agro-industrial systems for monitoring the hydration of crops, in multi-beam wireless communication systems and other applied tasks that require the use of technologically advanced and energy-efficient terahertz radiation sensors. Antenna arrays and metasurfaces that provide real-time routing of radio signals are designed to improve the robustness of wireless connections in next-generation communications networks.

The use of the methods described in this dissertation for calculating the radio-physical properties of terahertz antenna arrays integrated with Schottky diodes

of the proposed technological designs can provide benefits at the stage of design, manufacturing and practical use in real terahertz systems. The obtained developments were applied to the creation and implementation of commercially available diode detectors in the 110–170 GHz range by «Tirphotonics» LLC, which justifies the successful **implementation result**.

Methodology and research methods. As part of the ongoing research, the sensitivity of a waveguide receiver made on the basis of a planar Schottky diode was assessed by measuring the power equivalent to noise in direct detection mode and using microwave reflectometry. To measure the direct current characteristics of a diode with a Γ-shaped anode bridge, the long line method was used. Also, to analyze the current-voltage and impedance-voltage characteristics of a planar Schottky diode, the Lambert W_0-function apparatus was used. Measurements of the time and amplitude characteristics of dynamic blocking in point-to-point wireless connection scenarios were carried out when transmitting a terahertz signal between the base station and the user device in direct and indirect visibility communications. When implementing such a scenario, dynamic blocking in the communication channel was carried out by a person moving across the signal propagation line. The analysis of the parameterized unit cell model of the reconfigurable antenna array with microcontacts Schottky was carried out using the finite element method and the results of the impedance-voltage characteristic analysis.

Provisions presented for defense:

1. The use of a Γ-shaped suspended anode bridge in the design of a planar Schottky diode ensures twofold miniaturization without increasing parasitic capacitive coupling in its structural elements. The total shunt capacitance is 3 fF for a bridge length of 2 μm, a height and width of the semiconductor mesa of 2 and 15 μm, respectively, and a Schottky contact area of 0.785 μm^2.

2. The design of a matrix Schottky diode detector with line-by-line frequency division of channels and a response readout system based on a microwave

reflectometer provides a gain in performance proportional to the number of lines of the detector with a twofold deterioration in sensitivity. The detector pixel at 150 GHz has an noise equivalent power of no more than 160–320 pW $Hz^{-0.5}$, a dynamic range of 30 dB and 40 dB with Schottky contact diameters of 1 μm and 3 μm, respectively.

3. The model of the unit cell of a reconfigurable antenna array with Schottky microcontacts, which takes into account the impedance-voltage characteristics of the contact in explicit form using the Lambert W_0-function and solving the Poisson's equation for a given doping profile of the semiconductor contact layer, makes it possible to design devices with discrete and continuous pattern formation in the reflected light. The error in calculating reflectivity is no more than 1 dB in the range 132–162 GHz.

The degree of reliability of the obtained results. The main results of the work were reported at 5 international conferences and 1 interuniversity conference. At the same time, 3 reports were presented orally and 3 reports were presented in poster format.

Publications. The main results on the topic of the dissertation are presented in 16 printed publications, 14 of which were published in journals included in the Scopus and Web of Science lists.

The author's personal contribution to the research

The author took an active part in:

- Formulation of the topic, purpose setting and research tasks.
- Setting up and performing experiments to measure the time and amplitude characteristics of dynamic blockage in point-to-point wireless connection scenarios, noise equivalent power (NEP) of a waveguide receiver made on the basis of a planar Schottky diode.
- Development of a matrix waveguide receiver design with an effective operating

frequency range of 130–160 GHz, based on diode elements using a microwave reflectometer and an analog CMOS multiplexer, design of a 2-bit IRS with multi-state beamforming in reflected light at low frequencies in the range 130–160 GHz based on planar Schottky diodes.

- Processing and analysis of data obtained as a result of experiments, numerical and analytical modeling.
- Presentation of research results at international conferences with oral and poster presentations.
- Preparation of publications in international peer-reviewed publications, including those included in the Scopus and Web of Science lists.

Contents

The dissertation consists of an introduction, a literature review, 3 chapters, a conclusion and a reference list. The full volume of the dissertation is 92 pages, of which 80 pages of text, including 32 figures and 7 tables. The reference list includes 65 titles on 7 pages.

In the **introduction** the rationale for the relevance of the topic, scientific novelty and practical relevance of the dissertation work is stated, the purpose and tasks are formulated, the scientific novelty of the research is shown, and the scientific provisions submitted for defense are presented.

The **first chapter** presents a brief review of the literature on reconfigurable terahertz antenna arrays with diode elements capable of providing fast beamforming, the state of manufacturability of similar designs described in scientific publications, as well as the problems of using such devices in the terahertz range and ways to overcome them. Antenna solutions using active elements with lower performance are also considered.

The **second chapter** presents the design of a planar Schottky diode with a Γ-shaped suspended anode bridge, which optimizes its parasitic parameters. The

main parameters of diodes were measured for direct current and their current-voltage characteristics were analyzed using the Lambert W_0-function apparatus. Also, using the apparatus of this function, the Schottky microcontact was analyzed and an analytical model describing its impedance-voltage characteristic was presented. The values of the Y-parameters were obtained for a planar Schottky diode built into a coaxial transmission line. The design of a matrix diode Schottky detector with line-by-line frequency division of channels and a response readout system based on a microwave reflectometer has been developed. The noise equivalent power to with and without a microwave reflectometer, as well as the dynamic ranges of diodes with Schottky microcontacts, were measured and analyzed. The design of a waveguide detector based on a planar Schottky diode has been developed. Prototypes of antenna arrays made of dielectric with low and high dielectric values are presented, their main characteristics are measured and analyzed.

The **third chapter** presents a propagation model for a highly directional indoor communication channel. An extensive campaign of measurements of dynamic blocking characteristics in line-of-sight and non-line-of-sight communications has been carried out. Using the apparatus of the characteristic matrix of a stratified medium, the dielectric properties of sheet glass, drywall and porous aerated concrete in the terahertz range were studied. For the latter material, a model has been compiled that takes into account the porosity of its filling. A model of the unit cell of a reconfigurable antenna array with Schottky microcontacts is presented, taking into account the impedance-voltage characteristics of the contact in explicit form using the Lambert W_0-function. Using Floquet port analysis and the finite element method, it is shown that such an unit cell as part of an antenna array is capable of providing the ability to design devices with discrete and continuous beamforming in reflected light at frequencies in the terahertz range.

The **conclusion** presents the main results obtained as a result of the dissertation research.

Approbation

C1. Efficiency of a Microwave Reflectometry for Readout of a THz Multipixel Schottky Diode Direct Detector // 7th International School and Conference on Optoelectronics, Photonics, Engineering and Nanostructures «Saint Petersburg OPEN 2020», Санкт Петербург, Россия, 27–30 апреля 2020г.

C2. Разработка и изготовление микрополосковой СВЧ обвязки для I\Q - модулятора на базе ППВМ // Межвузовская научно-техническая конференция студентов, аспирантов и молодых специалистов им. Е.В. Арменского, Москва, Россия, 10–17 марта 2021г.

C3. Towards multipixel THz Schottky diode detector with a single RF output line // 8th International School and Conference on Optoelectronics, Photonics, Engineering and Nanostructures «Saint Petersburg OPEN 2021», Санкт Петербург, Россия, 25–28 мая 2021г.

C4. Unit cell model of a terahertz intelligent reflecting surface with Schottky microcontacts // 35th European Modeling & Simulation Symposium (EMSS 2023), Афины, Греция, 18-20 сентября 2023г.

List of author's publications

A1. Empirical blockage characterization and detection in indoor sub-THz communications / A. Shurakov, D. Moltchanov, **A. Prikhodko**, A. Khakimov, E. Mokrov, V. Begishev, I. Belikov, Y. Koucheryavy, G. Gol'tsman // Computer Communications. — 2023. — T. 201. — C. 48—58.

A2. Dynamic Blockage in Indoor Reflection-Aided Sub-Terahertz Wireless Communications / A. Shurakov, P. Rozhkova, A. Khakimov, E. Mokrov, **A. Prikhodko**, V. Begishev, Y. Koucheryavy, M. Komarov, G. Gol'tsman // IEEE Access. — 2023. — T. 11. — C. 134677—134689.

A3. Integrated Circuit of an Intelligent Reflecting Surface for sub-THz Wireless Communication / A. Shurakov, **A. Prikhodko**, I. Belikov, A. Razakova, G. Gol'Tsman // 2023 IEEE 18th International Conference on Nano/Micro Engineered and Molecular Systems (NEMS). — IEEE. 2023. — C. 183—187.

A4. Towards multipixel THz Schottky diode detector with a single RF output line / **A. Prikhodko**, I. Belikov, D. Mikhailov, A. Shurakov, G. Goltsman // Journal of Physics: Conference Series. T. 2086. — IOP Publishing. 2021. — C. 012063.

A5. Efficiency of a microwave reflectometry for readout of a THz multipixel Schottky diode direct detector / A. Shurakov, **A. Prikhodko**, D. Mikhailov, I. Belikov, N. Kaurova, B. Voronov, G. Goltsman // Journal of Physics: Conference Series. T. 1695. — IOP Publishing. 2020. — C. 012156.

A6. Planar Schottky diode with a Γ-shaped anode suspended bridge / A. Shurakov, D. Mikhailov, I. Belikov, N. Kaurova, T. Zilberley, **A. Prikhodko**, B. Voronov, I. Vasil'evskii, G. Goltsman // Journal of Physics: Conference Series. T. 1695. — IOP Publishing. 2020. — C. 012154.

A7. Unit cell model of a terahertz intelligent reflecting surface with Schottky microcontacts / **A. Prikhodko**, T. Yaropolov, A. Shurakov, G. Gol'tsman //

Proceedings of the 35th European Modeling & Simulation Symposium (EMSS 2023). — CAL-TEK. 2023.

A8. Blockage Attenuation and Duration Over Reflected Propagation Paths in Indoor Terahertz Deployments / **A. Prikhodko**, A. Khakimov, E. Mokrov, V. Begishev, A. Shurakov, G. Gol'tsman // International Conference on Distributed Computer and Communication Networks Proceedings of the International Conference on Distributed Computer and Communication Networks: Control, Computation, Communications (DCCN 2023). Lecture Notes in Computer Science. — Springer. 2023. — С. 423—434.

A9. Digital phase shifter arrays for beamforming in sub-THz communications / A. Shurakov, A. Lvov, **A. Prikhodko**, G. Gol'tsman // The 5-th lnternational Conference "Terahertz and Microwave Radiation: Generation, Detection and Applications" (TERA-2023). — 2023. — С. 91—92.

A10. Nondestructive KPFM-assisted Quality Control in Fabrication of GaAs High-Speed Electronics / A. Shurakov, N. Kaurova, I. Belikov, T. Zilberley, **A. Prikhodko**, B. Voronov, G. Gol'tsman // arXiv preprint arXiv:2212.01474. — 2022.

A11. Membrane-integrated planar Schottky diodes for waveguide mm-wave detectors / A. Shurakov, I. Belikov, **A. Prikhodko**, D. Mikhailov, G. Gol'tsman // Microwave and Telecommunication Technology. — 2021. — Т. 3. — С. 34.

A12. *Приходько А.* Разработка и изготовление микрополосковой СВЧ обвязки для I\Q - модулятора на базе ППВМ // Межвузовская научно-техническая конференция студентов, аспирантов и молодых специалистов им. Е.В.Арменского. — М.: МИЭМ НИУ ВШЭ. 2021. — С. 214—216.

References

1. *Schottky W.* Zur halbleitertheorie der sperrschicht-und spitzengleichrichter // Zeitschrift für Physik. — 1939. — Т. 113. — С. 367—414.
2. *Schottky W.* [и др.]. Quantitative treatment of the space charge and boundary-layer theory of the crystal rectifier // Wiss. Veroff. Siemens-Werken. — 1939. — Т. 18. — С. 225—291.
3. *Siegel P. H.* Terahertz technology // IEEE Transactions on microwave theory and techniques. — 2002. — Т. 50, № 3. — С. 910—928.
4. Low Noise 1 THz–1.4 THz Mixers Using Nb/Al-AlN/NbTiN SIS Junctions / A. Karpov [и др.] // IEEE Transactions on Applied Superconductivity. — 2007. — Т. 17, № 2. — С. 343—346.
5. *Shurakov A.* [и др.]. Superconducting hot-electron bolometer: from the discovery of hot-electron phenomena to practical applications // Superconductor Science and Technology. — 2015. — Т. 29, № 2. — С. 023001.
6. THz diode technology: Status, prospects, and applications / I. Mehdi [и др.] // Proceedings of the IEEE. — 2017. — Т. 105, № 6. — С. 990—1007.
7. Terahertz Direct Detection in YBa2Cu3O7-x Microbolometers / A. Hammar [и др.] // IEEE Transactions on Terahertz Science and Technology. — 2011. — Т. 1, № 2. — С. 390—394.
8. *Tang A. Y.* [и др.]. Impact of eddy currents and crowding effects on high-frequency losses in planar Schottky diodes // IEEE Transactions on Electron Devices. — 2011. — Т. 58, № 10. — С. 3260—3269.
9. Ti/Au/n-GaAs planar Schottky diode with a moderately Si-doped matching sublayer / A. Shurakov [и др.] // Microelectronic Engineering. — 2018. — Т. 195. — С. 26—31.

10. *Pearson J. C.* [и др.]. Instrumentation for THz spectroscopy in the laboratory and in space // IEEE Journal of Microwaves. — 2021. — Т. 1, № 1. — С. 43—54.

11. IceCube: spaceflight demonstration of 883-GHz cloud radiometer for future science / D. L. Wu [и др.] // CubeSats and SmallSats for Remote Sensing III. Т. 11131. — SPIE. 2019. — С. 1113103.

12. *Mehdi I.* THz Applications: Devices to Space System // Fundamentals of Terahertz Devices and Applications. — John Wiley & Sons, 2021. — Гл. 13. С. 511—545.

13. Terahertz spectroscopy and imaging: A review on agricultural applications / L. Afsah-Hejri [и др.] // Computers and Electronics in Agriculture. — 2020. — Т. 177. — С. 105628.

14. Toward 6G networks: Use cases and technologies / M. Giordani [и др.] // IEEE Communications Magazine. — 2020. — Т. 58, № 3. — С. 55—61.

15. Wireless communications through reconfigurable intelligent surfaces / E. Basar [и др.] // IEEE access. — 2019. — Т. 7. — С. 116753—116773.

16. A Promising Technology for 6G Wireless Networks: Intelligent Reflecting Surface / W. Long [и др.] // Journal of Communications and Information Networks. — 2021. — Т. 6, № 1. — С. 1—16.

17. *Yang F.* [и др.]. Terahertz reconfigurable intelligent surfaces (RISs) for 6G communication links // Micromachines. — 2022. — Т. 13, № 2. — С. 285.

18. Reconfigurable intelligent surfaces for wireless communications: Overview of hardware designs, channel models, and estimation techniques / M. Jian [и др.] // Intelligent and Converged Networks. — 2022. — Т. 3, № 1. — С. 1—32.

19. Intelligent reflecting surface: Practical phase shift model and beamforming optimization / S. Abeywickrama [и др.] // IEEE Transactions on Communications 2020. — Т. 68, № 9. — С. 5849—5863.

20. *Costa F.* [и др.]. Electromagnetic model of reflective intelligent surfaces // IEEE Open Journal of the Communications Society. — 2021. — Т. 2. — С. 1577—1589.

21. Intelligent metasurfaces with continuously tunable local surface impedance for multiple reconfigurable functions / F. Liu [и др.] // Physical Review Applied. — 2019. — Т. 11, № 4. — С. 044024.

22. *Zhu B. O.* [и др.]. Active impedance metasurface with full 360 reflection phase tuning // Scientific reports. — 2013. — Т. 3, № 1. — С. 3059.

23. Reconfigurable intelligent surface-based wireless communications: Antenna design, prototyping, and experimental results / L. Dai [и др.] // IEEE access. — 2020. — Т. 8. — С. 45913—45923.

24. Electro-thermal model for multi-anode Schottky diode multipliers / A. Y. Tang [и др.] // IEEE Transactions on Terahertz Science and Technology. — 2012. — Т. 2, № 3. — С. 290—298.

25. The physical topological modeling of single radiation effects in submicron ultrahigh-frequency semiconductor diode structures with taking in account the heating of an electron-hole gas in the charged particle track / E. Tarasova [и др.] // Proceedings of the 33th European Modeling & Simulation Symposium (EMSS 2021). — CAL-TEK. 2021.

26. Air-bridged Schottky diodes for dynamically tunable millimeter-wave metamateria phase shifters / E. Vassos [и др.] // Scientific Reports. — 2021. — Т. 11, № 1. — С. 5988.

27. Analytical extraction of a Schottky diode model from broadband S-parameters / A. Y. Tang [и др.] // IEEE transactions on microwave theory and techniques. — 2013. — Т. 61, № 5. — С. 1870—1878.