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As a manuscript

Semyon A. Presnyakov

Investigation and development of millimeter and submillimeter-wave slow-wave structures

Dissertation summary
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Natalia Pavlovna Kravchenko

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Relevance

The continuous development of science and technology sets new standards for the parameters and characteristics of our instruments and devices. One of the most important areas of technology in modern society is communication. There are many different aspects that are considered in the fields of research that study technologies and issues of communication, and one of them is the creation and development of new amplifying devices operating in little-studied frequency bands, such as millimeter and especially submillimeter (terahertz) ranges. Potential applications include high-speed communications, detection of hidden weapons or other types of threats, high-resolution remote imaging, chemical spectroscopy, materials research, deep space exploration and communications, biological spectroscopy, and biomedical diagnostics [1]. In particular, the use of the terahertz range in biomedical diagnostics of eye diseases using reflectometry was investigated during the postgraduate studies in the work [2].

Attempts to create such amplifying devices based on vacuum tubes are of interest to researchers because of their high power density, which is unattainable for modern solid-state electronics. One of the key components of amplifying vacuum electronic devices are slow-wave structures (SWSs). Many key characteristics of amplifying devices, such as output power and operating range, depend on the correct selection of the SWS. One of the most common electro-vacuum amplifying devices is a traveling wave lamp (TWT). When creating broadband (up to 1-2 octaves) TWTs, classical spiral SWSs have always been traditionally used, however, the use of this type of SWS in millimeter and submillimeter bands is very limited due to small heat sink of this type of AP: for the middle part of the centimeter range, spiral APs allow reaching output power up to ~ 1 kW, and at frequencies of the order of 18 GHz - only about 100 W. The use of all-metal SWSs such as, for example, the chains of coupled cavities (CCCs), makes increasing of the average power to 5-8 kW possible due to their good heat dissipation, however, the operating range for this type of structure is approximately 8% (maximum 17%) due to their resonant properties. In addition, significant difficulties may arise for CCC-type SWSs in their manufacture at frequencies above 100 GHz due to the complex configuration of individual elements, which limits their applicability to the current capabilities of existing microfabrication technologies. In this regard, the study and development of new types of structures, as well as the modification of existing types of SWSs, the creation of methods for calculating their characteristics, as well as the study of the physical mechanisms of the interaction of an electron beam with a wave in small vacuum electron devices are relevant tasks in the development of amplifying devices in millimeter and submillimeter range of electromagnetic waves.

Thus, the solution of the above tasks will allow obtaining new scientific and technical results in the field of creation and development of sources of coherent electromagnetic radiation and radio systems of the millimeter and submillimeter range and will accelerate the development of technologies in the field of communications, spectroscopy, diagnostics and other applications.

State of the art

The current state of the art in millimeter and submillimeter wave SWSs is an active area of research and development. Despite significant achievements, there are still challenges and opportunities for further development. Currently, the following problems can be identified:

1. **Research of SWS designs.** The study of various types of SWS in the millimeter and submillimeter ranges is constantly in the field of view of researchers. This includes various types of SWSs such as modified helixes, periodic systems, metamaterial systems, and waveguide systems. The focus is on designing and optimizing these systems to achieve the desired slow-wave effects, impedance matching, and improved performance in the millimeter and submillimeter wavelength ranges [1, 3].
2. **Manufacturing technologies**. The development of technologies for the manufacturing of SWSs in the millimeter and submillimeter ranges is an active area of research. Technologies such as micromachining, lithography, additive manufacturing and advanced material deposition techniques are being studied to create complex and precise systems with the required characteristics. Improvement in manufacturing technology is essential to achieve miniaturization, loss reduction and the ability to integrate slow-wave structures with other components and

systems [1, 4, 5].

3. **Choice of materials**. Materials engineering plays an important role in the creation of SWSs in the millimeter and submillimeter ranges. New materials with low losses and high electrical conductivity in these frequency ranges are being investigated. Materials such as high-resistance silicon, gallium nitride (GaN), diamond and various composite materials are being researched for their suitability for efficient slow wave transmission and loss minimization [6, 7].
4. **Design and simulation**. Design and simulation of SWSs in the millimeter and submillimeter ranges play a fundamental role in their development. Advanced design and simulation tools are used, such as electromagnetic simulation software using finite element methods (FEM) and finite difference time domain methods (FDTD). These tools allow to analyze and optimize the electromagnetic behavior and performance of slow-wave structures [8–10].
5. **Applications and systems**. The development of SWSs in the millimeter and submillimeter ranges is determined by a variety of applications, such as communication systems, radar systems, measuring equipment, sensory devices, sensors. These frequency ranges offer unique opportunities for high quality images, high bandwidth communications and accurate detection in challenging environments. Researchers are studying how SWSs can be integrated into these systems and customized to meet the specific requirements of a variety of applications [3, 11].

In general, the current state of the art in millimeter and submillimeter SWS development is characterized by active research, improvements in manufacturing technologies and materials engineering, and the development of design and simulation tools. Efforts continue to be made to improve performance, reduce losses, miniaturization, increase heat dissipation and explore new applications in these frequency ranges.

Purpose and objectives of the study

The purpose of this work is to study the physical, stuctural and technological features of SWSs in the millimeter and submillimeter ranges, as well as to create an algorithm for calculating such SWSs to improve their electrodynamic characteristics.

Within the framework of this study, the following tasks were solved:

- Analysis of SWSs of millimeter and submillimeter ranges, as well as the main physical, structural and technological problems that arise when creating amplifying vacuum electron devices based on them.
- Development of a method for describing the SWS cell using the theory of multipole networks, taking into account the electromagnetic energy transmission channels that arise in the presence of a transit channel for an electron beam, for calculating electrodynamic characteristics, such as the slowing factor, reactive attenuation and characteristic impedance.
- Development of algorithms for calculating the parameters of the SWS based on the results of 3D modeling and analysis of the electrodynamic characteristics of the SWS in the millimeter and submillimeter ranges.
- Analysis of the possibility of expanding the bandwidth of an axially symmetric SWS of the CCC-type in the millimeter range.

Study highlights

As a result of this study, the following main statements can be made:

1. When developing SWSs in the millimeter and submillimeter ranges of electromagnetic waves, taking into account the transit channel when calculating the electrodynamic characteristics plays an important role due to the increasing relevance of multibeam devices, as well as structures using sheet electron beams. Accounting for the transit channel has a significant effect on such electrodynamic parameters as dispersion characteristics (including the position and width of the passbands) and the characteristic impedance of the SWS.

2. A method for describing the SWS cell is proposed, which makes it possible to take into account the presence of a transit channel for an electron beam inside the SWS using the transfer matrix of a four-port network (octupole). The electrodynamic characteristics of the SWS are determined by finding the eigenvalues and eigenvalues of the transmission matrix that describes the given structure. According to the algorithm presented in the paper for finding the electrodynamic

characteristics of the SWS in the millimeter and submillimeter range, the slowing factor, reactive attenuation and characteristic impedance are calculated taking into account the presence of the additional channel for transmitting electromagnetic energy that arise in the presence of a passage channel for the electron beam.

3. By changing the opening angle of the slot channel in a CCC-type SWS, the possibility of controlling the bandwidth is shown. With an increase in the opening angle, it is possible to achieve a 2.5-fold expansion of the band with an increase in the angle by 90 degrees, and in case when the resonator and slot bands merge, up to an octave. However, this reduces the characteristic impedance. A possible solution to this problem is to change the shape of the SWS slot.

Scientific novelty

The scientific novelty of the presented dissertation work is as follows:

- A method for calculating the electrodynamic characteristics of the SWS has been developed, taking into account the presence of two channels for transmitting electromagnetic energy inside the SWS using a four-port network transmission matrix. The error of this method does not exceed $5 \cdot 10^{-5}$% for the characteristic impedance and does not exceed the value of the computational error for the slowing factor in comparison with the classical method of finding the dispersion of transmission lines.
- As a result of the analysis of the physical, structural and technological features of devices in the millimeter and submillimeter ranges and the calculation of the electrodynamic characteristics of the SWS in these ranges, the importance of taking into account the presence of a transit channel in the SWS model is shown.
- The influence of the opening angle of the slotted channel in an axially symmetric the CCC-type SWS of millimeter range with bean-shaped slots in order to control the width of the passband has been studied, the possibility of its expansion up to an octave has been demonstrated.

Dissertation structure

The dissertation consists of an introduction, 3 chapters, a conclusion, a bibliographic list and an appendix. The total volume of the dissertation work is 162 pages, including 75 figures and 6 tables.

The **first chapter** of the dissertation discusses the features of creating amplifying devices in the millimeter and submillimeter ranges. A review of the current state of the art and perspectives for the creation of devices in the aforementioned frequency ranges has been carried out. The mechanisms of interaction in vacuum electron amplifiers are described. The design and principle of operation of the TWT, as well as the main basic structures of the SWSs used in the TWT are considered. The physical, structural and technological problems that arise when creating devices in the millimeter and submillimeter wavelength ranges are analyzed. A review of the main microfabrication technologies applicable for the creation of SWS in the millimeter and submillimeter ranges is carried out, their advantages and disadvantages are analyzed, and examples of the application of these technologies for the creation of vacuum electron devices are given. The conditions for the creation of a magnetic field inside the SWS, necessary to keep the electron beam inside it, are given. Possible designs of the cathode for devices in the millimeter and submillimeter ranges are presented. The necessity of taking into account the difficulties of creating complex electrodynamic structures in the indicated ranges and possible ways of solving some of the problems that arise when creating SWSs in the millimeter and sub-millimeter ranges are noted.

In the **second chapter** of the dissertation, the methodology for calculating the electrodynamic characteristics of the SWSs in the millimeter and submillimeter ranges is considered. The main characteristics of the SWSs and the methods of obtaining them are analyzed. A method is presented for describing the SWS cell using a multipole, which makes it possible to take into account the presence of a transit channel for an electron beam inside the SWS using the transmission matrix of a four-port network. The electrodynamic characteristics of the SWS are determined by finding the eigenvalues and eigenvectors of the transmission matrix that describes the given structure.

The adequacy of the presented method was assessed by comparison with the classical method for calculating the dispersion of nonlinear transmission lines.

The methods used to obtain the components of the matrix of a 2N-terminal network describing the SWS are considered. Partial domain methods and global methods are analyzed. The methods used for numerical modeling of Maxwell's equations in 3D modeling of the SWS are described. Their advantages and disadvantages for solving electrodynamic problems are given.

The **third chapter** presents the calculation results of the electrodynamic characteristics of SVs in the millimeter and submillimeter ranges using the developed method and analyzes the electrodynamic characteristics taking into account the presence of a transit channel in the calculation. The SWSs of the "folded waveguide" type of two different configurations in the millimeter and submillimeter ranges, as well as millimeter axially symmetric and rectangular the CCC-type SWSs were considered. The possibility of extending the bandwidth for an axially symmetrical CCC-type SWS is analyzed.

In **conclusion**, the main results obtained in the course of this work are presented.

The **appendices** provide a transition matrix from an impedance matrix to a 4x4 transmission matrix, as well as listings of programs for calculating electrodynamic characteristics with 2 and 4 ports for transmitting electromagnetic energy.

Main results of the study

As a result of this work, the relevant task of studying the physical, structural, and technological features of SWSs in the millimeter and submillimeter ranges, as well as the creation of an algorithm for calculating such SWSs to study the possibilities of improving their electrodynamic characteristics, was completed.

The main results of this work::

1) A review of the current state of the art and perspectives for the creation of devices in the indicated frequency ranges was carried out. The mechanisms of electron-wave interaction in vacuum electron amplifiers are described. the physical,

structural, and technological problems that arise when creating devices in the millimeter and submillimeter wavelength ranges are analyzed.

a) A review of the main microfabrication technologies applicable for producing SWSs in these ranges is carried out, examples of their application in the context of the research topic are given. It is shown that the main problems that arise when creating devices in the millimeter and submillimeter ranges are associated with the small overall dimensions of the manufactured structures, which leads to a tendency to simplify them with an increase in the operating frequency. The necessity of creating new SWS designs, more adapted to fabrication using existing microfabrication methods, as well as having sufficient heat dissipation, is shown.

b) The effect of device miniaturization on the choice of a magnetic focusing system and cathode design is considered. It is shown that taking into account the presence of a transit channel when designing an SWS in the millimeter and submillimeter ranges becomes especially important due to an increase in the current density inside the device, as well as the prospects for the use of multi-beam structures or sheet beams.

2) A method for describing the SWS cell using a multipole is proposed. This method allows to take into account the presence of a transit channel for an electron beam inside the SWS using the transmission matrix of a four-port network. The electrodynamic characteristics of the SWS are determined by finding the eigenvalues and eigenvectors of the transmission matrix that describes the given structure.

a) A review of the methods used to obtain the components of the matrix of a 2N-terminus describing the SWS was carried out. Partial domain methods and global methods are analyzed. The methods used for numerical modeling of Maxwell's equations in 3D modeling of the SWS are described. Their advantages and disadvantages for solving electrodynamic problems are given.

b) An algorithm is proposed for finding the electrodynamic characteristics of SWSs in the millimeter and submillimeter range through the transmission matrix of a four-port network, which allows to calculate their deceleration coefficient, reactive attenuation, and characteristic impedance, taking into account the presence of two electromagnetic energy transmission channels that arise in the presence of a transit channel for the electron beam. The adequacy of the method is assessed based on comparison with the already used method for calculating the dispersion characteristics of nonlinear transmission lines. The calculated error of the proposed method does not exceed $5 \cdot 10^{-5}$ % for the characteristic impedance and does not exceed the value of the computational error for the slowing factor compared to the classical method for finding the dispersion of transmission lines.

3) The electrodynamic characteristics of the "folded waveguide" type SWS in the millimeter and submillimeter bands of two different configurations are calculated and the dependences of the electrodynamic characteristics are analyzed, taking into account the presence of a transit channel.
   a) For configuration No. 1, two models were considered with the periods of 5.5 and 1 mm, calculated at frequencies from 40 to 50 GHz and from 275 to 375 GHz, respectively. The presence of a transit channel leads to a shift in the peaks of the characteristic impedances, while with a miniaturization of the SWS and, accordingly, an increase in the operating frequency, this effect becomes more pronounced. When implementing this configuration of the SWS at high frequencies (model No. 2), the imaginary part of the characteristic impedance becomes most pronounced, which has limited significance in assessing the interaction of the beam with the wave [12]. From the graphs of dispersion characteristics, it can be seen that taking into account the transit channel for a given configuration affects the type of dispersion, as well as the position of the passbands and attenuation, while for a higher frequency case (model No. 2) this effect is more pronounced.
   b) b) For configuration No. 2, three models were considered with periods of 810, 360 and 90 μm at W-band (75-110 GHz), G-band (110-300 GHz) and 0.6 to 1.1 THz, respectively. For all models of this configuration, the presence of the transit channel led to a shift to higher frequencies in the peaks of the real part of the

characteristic impedance and the curve of the slowing factor by approximately 1%. At the same time, for models No. 2 and No. 3, an additional area of small attenuation appeared on the graphs of dispersion characteristics between the working bands of the SWS.

4) The electrodynamic characteristics of the CCC-type axially symmetrical SWS of were calculated in the range from 10 to 30 GHz, and the dependence of the electrodynamic characteristics of the SWS on the presence of a transit channel was analyzed.
   a) The presence of a transit channel in the model of the CCC-type axially symmetrical SWS shifts the peaks of the characteristic impedance values. The imaginary part of the characteristic impedance, when taking into account the transit channel, is shifted to the negative region, i.e., it can be concluded that the characteristic impedance will have a more capacitive character. This increases the values and expands the reactive attenuation bands and narrows the bandwidth. Also, the addition of a passage channel can lead to the appearance of additional resonances in the dispersion characteristic due to the resonant nature of the SWS.
   b) The dependence of the bandwidth of the CCC-type SWS on the slot opening angle for an axially symmetric CCC-type SWS in the range from 4 to 25 MHz wass analyzed. The possibility of expanding the bandwidth of the SWS by a factor of 2.5 with an increase in the slot opening angle by 90 degrees is shown; in this case, when the bands are merged, it is possible to obtain a working band with a width of up to an octave. However, the consequence of this is a drop in the characteristic impedance, while a possible solution to this problem is to change the shape of the SL slot.
5) A rectangular SWS of the CCC-type was considered in the range from 30 to 60 GHz with a period of 2.5 mm with two variants for the transit channel shape: one suitable for the pencil beam and one suitable for the sheet beam.
   a) The presence of a transit channel in such SWS also shifts the peaks of the characteristic impedance values along the frequency axis due to the shift of the passbands inside the SWS. The real part of the characteristic impedance increases in

the passbands when the transit channel is taken into account.

b) The observed picture is in many respects similar to that obtained for axially symmetric SWSs: it is seen that the presence of a transit channel in the model increases attenuation and narrows the bandwidth, regardless of the channel shape used. Due to the resonant nature of this SWS, the additional resonances also appear in the dispersion characteristics.

Author's personal contribution

The author's personal contribution to the work consists in his direct participation in the formulation and solution of research problems, the creation of three-dimensional models of devices presented in the dissertation, numerical simulation and analysis of the results obtained. The author has developed a method for calculating the electrodynamic characteristics of the SWS, which is confirmed by certificates of state registration of the computer programs. The preparation of the main articles on the work was performed by author personally and with his direct participation.

Practical significance of the work

The results presented in the dissertation were obtained during the implementation of three two-year grants within the framework of the Academic Fund Program at HSE University as part of the Research Team Project "Electrodynamics of Slow-Wave Structures" (grant 17-05-0009, 2017-2018 years, grant 19-04-005, 2019-2020 years, grant 21-04-010, 2021-2022 years), as well as during the work during the internship on the topic "Submillimeter wave im-aging spectroscopy of cornea for the early detection of disease" at Aalto University (Espoo, Finland) as part of the "Academic Postgraduate Program".

In the course of work on the dissertation, certificates of state registration of the computer program were obtained:

1. №2016616989 "Calculation of the dispersion characteristics of slow-wave structures with one channel for the propagation of microwave energy based on the results of their three-dimensional modeling";
2. №2016616990 "Calculation of the dispersion characteristics of slow-wave

structures with four ports based on the results of their three-dimensional modeling";

3. №2016662704 "Calculation of slowing factor, reactive attenuation and characteristic impedance of a rectangular slow-wave structure of a "chain of coupled resonators" type with separation into cells along the coupling slots".

The electrodynamic characteristics of the SWS calculated using these programs can be used to develop compact amplifying devices in the high-frequency ranges of microwave radiation, while the interaction of the beam with the wave can be calculated using the difference theory of excitation of electrodynamic systems.

Approbation of the research results

The results obtained as a result of this work were presented by the author personally at major international and all-Russian conferences:

1. 2018 International Conference on Actual Problems of Electron Devices Engineering (APEDE'2018), «Modeling of discrete interaction processes in traveling-wave tube with resonator slow-wave structures of microwave and EHF ranges», Saratov, 27-28 September, 2018.
2. 2020 International Conference on Actual Problems of Electron Devices Engineering (APEDE'2020), «Theoretical Analysis of Coaxial-Radial Type Slow-Wave Structure Electrodynamic Characteristics and Its Modifications», Saratov, 24-25 September, 2020.
3. Interuniversity Scientific-Technical Conference of Students, Graduate Students and Young Professionals of E.V. Armensky, «Analysis of slow-wave structures used in millimeter range devices», Moscow, 17-29 February, 2016.
4. Interuniversity Scientific-Technical Conference of Students, Graduate Students and Young Professionals of E.V. Armensky, «Development of modeling methods and design tools for a traveling wave tube in the terahertz range», Moscow, 17 February – 1 March, 2017.
5. International Scientific Conference "Technologies of Information Society", «Amplification of electromagnetic waves in the millimeter range using slow-

wave structures such as "folded waveguide" », 16-17 March, Moscow, 2016.

6. International Scientific Conference “Technologies of Information Society”, «Analysis of slow-wave structures used in millimeter range devices », 24 March, Moscow, 2015.
7. International Scientific Conference “Technologies of Information Society”, «Simulation and Calculation of the Dispersion Characteristics of Slow-Wave Structures in the Microwave Range », Moscow, 15-16 March, 2017.
8. II All-Russian Joint Scientific Conference "Problems of Microwave Electronics" MIEM NRU HSE – "Innovative Solutions" Keysight Technologies, « Influence of a transit channel on the dispersion characteristics of axially symmetric resonator slow-wave structures», Moscow, 26-28 October, 2015.
9. 2019 8th Asia-Pacific Conference on Antennas and Propagation (APCAP-2019), «Building a Macromodel of the Satellite Antenna Equivalent Electrical Circuit», Incheon, 4-7 August, 2019.
10. Eighteenth International Vacuum Electronics Conference (IVEC-2017), «Investigation of “serpentine”-type slow-wave structures in the terahertz range», London, 24-26 April, 2017.
11. 2018 Asia-Pacific Microwave Conference (APMC-2018), «Investigation of Extension Limits of Main Passband of the “Chain of Coupled Resonators”-Type Slow-Wave Structure», Kyoto, 6-9 November, 2018.
12. 2017 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus), «Analysis of Dispersion Characteristics of Slow-Wave Structures Used in Terahertz Range Devices», Saint-Petersburg, 1-3 February, 2017.
13. 2016 International Siberian Conference on Control and Communications (SIBCON), «Model of “Chain of Coupled Resonators”-Type Slow-Wave Structure’s Cell Based on Equivalent Systems Method», Moscow, 12-14 May, 2016.
14. 2019 Systems of signals generating and processing in the field of on board communications, «Simulation of Resonator Slow-Wave Structures and Terminal Devices of TWT Sections in SHF and UHF Ranges», Moscow, 20-21 March, 2019.

15. 2023 Systems of Signal Synchronization, Generating and Processing in Telecommunications SYNCHROINFO-2023, «Software Complex "VEGA" for Designing cm- and mm-Wave TWT with Resonator Slow-Wave Structures», Yaroslavl, 1-3 July, 2019.
16. 2021 Systems of signals generating and processing in the field of on board communications, «Simulation Analysis of Interaction in O-Type Devices with CRL Type Slow-Wave Structures», Moscow, 16-18 March, 2021.
17. 2023 Systems of Signal Synchronization, Generating and Processing in Telecommunications SYNCHROINFO-2023, «Investigation of Electrodynamic Characteristics of the Millimeter Range Folded Waveguide Slow-Wave Structure», Pskov, 28-30 June, 2023.

Publications on the topic of the dissertation

The main results of the dissertation research are presented in 11 papers, 8 of which are indexed in Scopus/WoS.

Articles in journals indexed in Scopus/WoS:

1. Presnyakov S. Analysis of the dispersion characteristics of slow-wave structures with two microwave propagation channels / Kravchenko N., Mukhin S., Presnyakov S. (Translated from Russian). // Journal of Communications Technology and Electronics. 2017. Vol. 62. No. 7. P. 800-808
2. Presnyakov S. Extraction of Thickness and Water-Content Gradients in Hydrogel-Based Water-Backed Corneal Phantoms Via Submillimeter-Wave Reflectometry/ Tamminen A., Baggio M., Nefedova I., Sun Q., Presnyakov S., Ala-laurinaho J., Brown E., Wallace V., Macpherson E., Maloney T., Kravchenko N., Salkola M., Deng S., Taylor Z. // IEEE Transactions on Terahertz Science and Technology. 2021. Vol. 11. No. 6. P. 647-659

Publications in conference proceedings indexed in Scopus/WoS:

3. Presnyakov S. Simulation Analysis of Interaction in O-Type Devices with CRL Type Slow-Wave Structures,/ Kravchenko N., Kasatkin A., Presnyakov S., // in:

2021 Systems of signals generating and processing in the field of on board communications. IEEE, 2021. P. 1-4.

4. Presnyakov S. Theoretical Analysis of Coaxial-Radial Type Slow-Wave Structure Electrodynamic Characteristics and Its Modifications, / Presnyakov S., Kravchenko N., Kasatkin A., Mukhin S. // in: 2020 International Conference on Actual Problems of Electron Devices Engineering (APEDE' 2020). MATERIALS OF THE INTERNATIONAL SCIENTIFIC AND TECHNICAL CONFERENCE. Saratov. September 24-25, 2020. IEEE, 2020. P. 210-213
5. Presnyakov S. Building a Macromodel of the Satellite Antenna Equivalent Electrical Circuit, / Borisov N., Kravchenko N., Presnyakov S., Kasatkin A. // in: 2019 8th Asia-Pacific Conference on Antennas and Propagation (APCAP). Incheon, Korea (South): IEEE, 2019. doi P. 309-310.
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8. Presnyakov S., Model of "Chain of Coupled Resonators"-Type Slow-Wave Structure's Cell Based on Equivalent Systems Method, / Presnyakov S., Kravchenko N., Mukhin S. // in: 2016 International Siberian Conference on Control and Communications (SIBCON). Proceedings. M. : HSE, 2016. P. 1-4

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9. Presnyakov S. Millimeter-Band Slow-Wave Structures / Kravchenko N., Mukhin S., Presnyakov S. (In Russian) // T-Comm: Telecommunications and transport.

2015. Vol. 9. № 6. P. 57-63
10. Presnyakov S. Analysis of the slow-wave structures used in the millimeter range devices / Kravchenko N., Mukhin S., Presnyakov S., Kasatkin A. // T-Comm: Telecommunications and transport. 2016. Vol. 10. No. 8. P. 83-88
11. Presnyakov S. Analysis of the dispersion characteristics of the slow-wave structures used in the terahertz range devices (In Russian) / Kasatkin A., Presnyakov S., Kravchenko N., Mukhin S. // T-Comm: Telecommunications and transport. 2017. Vol. 11. № 1. P. 31-36

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8. Tsukerman I. Finite-Difference Time-Domain Methods for Electrodynamics , 2020. – PP. 357–423.

9. Weiland T. Finite Integration Method and Discrete Electromagnetism , 2003. – PP. 183–198.

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