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REVIEW OF MATHEMATICAL SUPPORT AND SOFTWARE FOR DESIGN OF SHF DEVICES

Introduction

Currently, machine design methods are widely used in the development of super high frequency (SHF) devices, which are based on existing knowledge bases and databases. The development of computer technology has allowed based on computers to design various complex distributed systems, which by classical analytical methods are impossible to implement. The known results on research of various SHF devices and their element base are presented in the form of databases of various subject areas [1, 2]. The growth of the speed of information transfer has led to the need to develop new approaches to the development of mathematical support (MS) and software. At the same time, the main problem is the lack of universal MS and software, which allows to solve a wide class of problems of designing various SHF devices relatively easily.

Formulation of the problem and its relevance

Currently, many SHF device design programs have been developed, which differ in mathematical support and the principles of software construction. This circumstance makes it difficult for designers of SHF equipment to make the right decision on the choice of appropriate software that best meets their requirements. To date, the choice of software is quite a complex problem and depends on the experience and qualifications of developers. As a rule, when choosing software the developers turn to various highly specialized experts, who quite often are also not able to give reasoned advice. Therefore, the selection of a class of application software packages (ASP) for SHF device design from the large variety of existing ASP is an important task.

Analysis of the latest research and publications

The analysis of recent publications [3-27] has shown that in the design of SHF devices, hundreds of different ASPs are currently used, developed based on different approaches to the development of models and methods of their analysis. This circumstance does not allow a relatively fast selection of the corresponding ASPs. In addition, when solving the design problems by different methods, often the results differ from each other. That is, the result depends on the used ASP. Thus, to get the best result it is sometimes required to solve the same problem by different methods. And after that the choice of the best result is made. Such a procedure requires high economic costs and does not guarantee the best result.

The purpose of this article is to familiarize designers of various SHF devices with the mathematical and computer-aided design software most suitable for the development of distributed systems.

Presentation of the main research material

Important criteria for choosing the right software are functionality, resource limitations, product cost, license restrictions, and availability of literature.

There are many mathematical programs that allow dealing with completely different technical problems - from a calculator working with numbers and letter expressions to applications that allow modeling whole dynamically changing systems. Let us consider some of them, which, as practical experience has shown [3–27], are most suitable for designing microwave devices. First, let us consider the basic concepts of mathematical support and software.

Basic information on mathematical support *and software*

Mathematical support. The design process of SHF devices consists of three main stages [2]: modelling, analysis, and optimization. When designing SHF systems, each of the stages can represent a complex problem, for which separate scientific research should be carried out. Successful solution of all three stages requires the development of appropriate MS and software. The MS is designed to implement control decisions, considered as a set of actions to achieve the set goals within the framework of the terms of reference.

The MS includes [1]:

1. Mathematical description (formalization) of tasks.
2. Mathematical models and their optimization.
3. Data prepared to describe the processes under study.
4. Algorithms for problem solving.
5. Analysis of models and algorithms based on the results of the work performed on the computer.

The mathematical support system should perform the following functions:

1. Implementation of any data processing procedures.
2. Composition of work programs for solving specific tasks from standard programs and original blocks.
3. Management of the process of solving tasks and their complexes.
4. Implementation of economic and mathematical methods of solving the optimization problems. MS must contain means of task programming automation, as well as means of assembling working models of specific systems from standard programs and their maintenance.

The development of the MS for the design of SHF devices involves the following steps:

1. Creating a model of the device or system.
2. Developing an enlarged algorithm.
3. Development of algorithms of separate elements of the MS.
4. Validation of algorithms (selection of computational tools, conducting programming, validation of the program).

SHF device design software mainly uses mathematical models (a set of mathematical objects (numbers, symbols, sets, etc.) and the relationships between them, reflecting in symbolic form the most important properties of the object for the study).

Mathematical modeling – the process of creating mathematical models and operating them in order to obtain the required information about the real object. Mathematical model must reflect the essence of the simulated SHF device. Requirements of universality, adequacy and economy (less expenditure of resources) are made to mathematical models. There are no general mathematical methods for finding an extremum of any kind function under arbitrary constraints. But for the target function and the system of constraints, which have certain properties, there are special methods investigated by mathematical programming.

Software. The software (Fig. 1) is understood as a set of programs that ensure the functioning of its technical means, the implementation of goals and objectives in the design of microwave devices.

The software includes OS (operating systems), ASP (application software packages) and programming systems (PS).

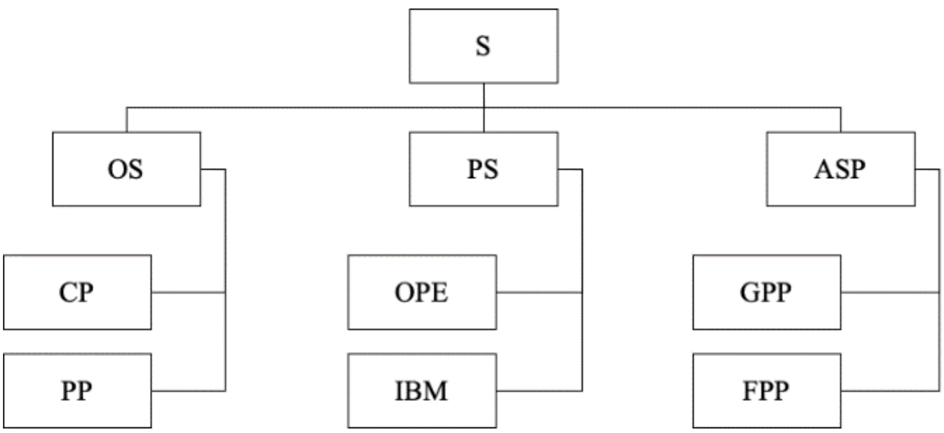

Fig. 1. Software structure: S – software; CP – controlling part; PP – processing part; GPP – general-purpose programs; FPP – functional purpose programs; OPE – organization of the process to be executed; IBM – information base maintenance

SHF device design software

The main purpose of the OS is to manage data, processes, tasks, and ensure human communication with the computer.

The software is closely related to the mathematical support (MS), as it is compiled based on the MS based on algorithms.

The software is closely related to the structure of the computer and implements the capabilities inherent in the hardware.

1.1. Modeling of three-dimensional electromagnetic structures (3D modeling)

Analysis of modern software [3–27] for automated design of three-dimensional (**3D**) electromagnetic structures for various purposes showed that one of the most recent most advanced 3D modeling packages is the **CST STUDIO SUITE 2021** package [20,27], which is a set of tools for design, modeling and optimization of three-dimensional electromagnetic systems. This software is a complete set of solutions for 3D modeling. The high level of simulation technologies of the CST package has been achieved by continuously improving the computational modules that summarize the experience of many years of research in the field of accurate and efficient computational methods. High reliability of results of CST STUDIO SUITE software package allows users to create virtual prototypes, which simulate behavior of real devices, thereby saving time and money during the development stage. Previously, computing modules were grouped into programs that had their original names: CST MICROWAVE STUDIO (CST MWS), CST EM STUDIO (CST EMS), CST PARTICLE STUDIO (CST PS), CST CABLE STUDIO (CST CS), CST PCB STUDIO (CST PCBS), CST BOARDCHECK (CST BC), CST MPHYSICS STUDIO (CST MPS), CST DESIGN STUDIO.

The current version of the CST STUDIO SUITE package includes the following modules:

- general-purpose time- and frequency-domain calculators for modeling low-frequency and high-frequency problems;
- full-wave calculator using integral equations;
- a module for eigenmodes and an asymptotic calculator;
- specialized Particle-In-Cell (PIC) algorithm;
- static and multiphysics calculator;
- many additional specialized computational modules.

The combination of the above modules provides an accurate and multifaceted approach to solve a wide range of problems. In some cases, a single problem can be solved using different computational methods. Universal CST approach allows to perform verification of the obtained data by comparing modeling results obtained with the use of different calculators in a single working environment. Such cross-checking increases the validity of the results and helps engineers identify errors in the design description or measurement process.

CST STUDIO SUITE includes calculators to solve problems overlapping the entire spectrum of electromagnetic radiation.

Qualitative modeling requires a project with a properly described structure. This means that the model must describe real objects and consider a wide range of electromagnetic effects affecting them. The CST STUDIO SUITE package includes tools for building and importing models from CAD systems to help the user build a correct design of the device under analysis.

Mixed analysis of electrical circuits and their structures in the time domain allows calculating electromagnetic fields resulting from interaction with nonlinear circuit elements, such as diodes or transistors. The broadband nature of time-domain analysis makes it possible to consider a wide range of harmonic components of the signal in the analysis.

Measured data such as near-field characteristics or S-parameters of semiconductor devices can also be imported into the CST STUDIO SUITE package. This makes it possible to integrate this data into the project and improve the description of the physical system.

The availability of realistic material models and discrete elements makes it possible to simulate SHF filters and matching devices.

Types of materials used in CST STUDIO SUITE:

- Dielectrics;
- Loss-loss metals;
- Anisotropic materials;
- Materials with a time dependence;
- Materials with a temperature dependence;
- Gradient materials;
- Dispersion materials;
- Non-linear materials;
- Coated materials;
- Radio absorbing materials;
- Materials made of thin flat layers;
- Materials with surface impedance;
- Surfaces with secondary electron emission;
- Materials with nonlinear temperature properties and biomaterials;
- Ferromagnetics;
- Graphene.

To apply a numerical simulation to the structure, a spatial discretization of the model under study is required. Adding additional cells increases the requirements to computing resources. This means that an algorithm that describes the shape of objects as accurately as possible using a minimum number of cells will be most useful. The CST STUDIO SUITE package includes tools for building rectangular, tetrahedral, and surface meshes, which are differently suited for modeling different situations.

To improve the accuracy of rectangular partitioning without a drastic increase in computational resource requirements, CST STUDIO SUITE uses Perfect Boundary Approximation (PBA) technology in its time domain calculator in relation to the rather general Finite Integral Method (FIT). The PBA technology keeps the computational speed at the level of the familiar rectangular partitioning, but for curved objects avoids excessive mesh refinement for a more accurate shape description.

With tetrahedral partitioning, additional advantages in modeling low-frequency and high-frequency structures can be obtained by using curvilinear cells. In addition, an original mesh optimization algorithm called True Geometry Adaptation is implemented in the calculator in the frequency domain. It projects a "cleaned" mesh back onto the original model, smoothing out the original mesh with faces, thus providing higher modeling accuracy.

The right choice of calculators plays a big role in 3D modeling. Below is a list of available computing technologies [20-27]:

- Transient solver – general tasks;
- Frequency domain solver – general tasks;
- Integral equation solver – electrically large structures, RCS;
- Asymptotic solver – electrically large structures, RCS;
- Eigenmode solver – volumetric resonance;
- Filter designer 2D – synthesis and analysis of SHF filters;
- Filter designer 3D – synthesis and analysis of SHF filters with coupled volume resonators;
- Electrostatic / magnetostatic solver – static tasks;
- Stationary current solver – constant current analysis;
- Transient solver – problems with nonlinear materials;
- Frequency domain solver – eddy currents, bias currents;
- System simulator - calculation of interference of a group of sources;
- PEEC solver – single-layer boards;
- TLM solver – signal integrity;
- 3D FEFD Solver – integrity of power circuits;
- EMC and SI Rule Check – checking EMC and SI restrictions on boards;
- Particle in cell solver – high frequency applications, SHF Devices;
- Wakefield Solver – acceleration technology.

The quality of the results and the speed of the simulation significantly depends on the choice of computational module. A calculator that works well on one type of model may perform poorly on other models. This is one of the reasons why the CST STUDIO SUITE package includes a wide range of different calculators. Because of this, you can always find the best tool for applications over a very wide frequency range (from constant fields to the optical range) and vastly different sizes (from nanoparticles to electrically large objects).

For example, a calculator using integral equations and an asymptotic calculator are ideal for problems such as antenna placement, estimating the effective reflective area of an object (RCS), where the electrical dimensions of a structure can number of hundreds or thousands of wavelengths.

Small resonant structures can be modeled more efficiently with an eigenmode calculator or a frequency domain calculator, which are designed specifically for analyzing devices such as filters or accelerating resonators.

Many simulated structures may consist of separate components, the qualitative simulation of which can only be done by different methods. For such cases, the technology of System Assembly and Modeling (SAM) is implemented, which allows to break a large structure into small objects, simulate them with the most suitable calculator, and then combine the data and get the full characteristics of the entire device.

High-performance and cloud computing. CST offers users various methods to accelerate computation [20, 27]: the use of multiprocessor platforms, support of graphic accelerators, cluster and distributed computing. These technologies allow to increase the capabilities of a workstation or to divide the simulated task among the nodes of a computational cluster. The use of high-performance computing methods is available for almost every type of task and any hardware configuration: from independent workstations to complex industrial clusters.

To provide users with the easiest and most efficient way to use these techniques, CST developed a special accelerator option licensing scheme. With it, engineers are able to combine different ways of high-performance computing, combining and tuning the necessary acceleration techniques.

For small companies, but with the need to process large tasks, the CST STUDIO SUITE package offers the use of remote calculation technology. With it, the model is transferred over a secure protocol to a high-performance server provider and the calculations are performed on its hardware. This means that users with the occasional need to process complex tasks can perform them without having to purchase and maintain large computing clusters.

Since building of high-performance hardware complexes requires considerable material expenses, customer representatives involved in purchasing and upgrading of computing systems are recommended to contact CST specialists to agree on the configuration best suited for the client's tasks. Also, CST cooperates with the hardware testing centers in order to guarantee that the selected configuration of equipment is most suitable for the CST STUDIO SUITE package. The CST STUDIO SUITE package supports combinations of high-performance computing methods. All of them can be implemented both on the local hardware platform and in the cloud.

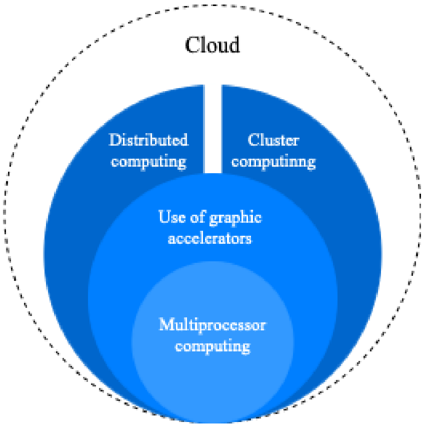

Fig. 2. Distribution of calculations in the analysis and synthesis of SHF devices

Automatic optimization. The characteristics of even the simplest device can be affected by a wide range of parameters [20, 27]. Optimization automates the process of adjusting the necessary variables in order to obtain values that meet the specified requirements. The built-in optimizers in all CST STUDIO SUITE modules can be used to adjust any parameter, including the geometric dimensions of the model, material properties, and the shape of the excitation signal.

Global and local optimizers are available in the CST STUDIO SUITE package. Local techniques search for solutions in the vicinity of the initial parameter value, so it is recommended to use them for models that are close to optimum. Global techniques operate over the full range of parameters, so they are much more practical than local optimizers in the case of roughly tuned models or complex structures.

Preliminary sensitivity analysis will significantly improve the performance of the CST Optimizer Trust Region Framework. This technique performs a rapid assessment of the impact on performance of small changes in model parameters, providing important initial conditions for the optimizer's operation. Sensitivity analysis will also allow the effect of manufacturing tolerances on the performance of the structure to be evaluated in just one computational cycle.

Optimizer databases used in the CST STUDIO SUITE package [20, 27]:

Local:

– Trust region framework;
– Nelder-mead simplex algorithm;
– Interpolated quasi-newton;
– Classic powell;
– Global;
– Genetic algorithm;
– Particle swarm;
– Evolutionary strategy with covariance matrix adaptation (CMA-ES).

The standard approach to organizing the design cycle assumes that the engineer himself chooses the necessary software modules and makes the necessary settings in them. The CST STUDIO SUITE package features a special project creation assistant designed to greatly simplify the setup and configuration of the simulation.

A special macro command language based on VBA and OLE technologies allows direct data exchange between different programs such as MATLAB®, MATCHAD or MS Excel®. The CST STUDIO SUITE package is also able to extract the HSPICE connection list which is automatically transferred to the Synopsis HSPICE package for further simulation of the chip-shell-board design including parasitic effects in the signal paths.

1.2. 3D design software for SHF filters and synchronizing devices (SHFF and SD)

The design and optimization of SHFF and SD is one of the key areas of CST STUDIO SUITE [20, 27]: the software contains a set of special simulation tools for each stage of SHFF and SD design, including initial topology synthesis, fine-tuning, thermal tuning and high-frequency breakdown analysis.

The starting point in the design process of SHFF and SD is the creation of a correct specification. Typically, the design requirements are not limited to pass and shutoff frequencies, but include definition of transmission and reflection zeros, Q-value, bandwidth ripple, size, thermal and cost requirements. In addition, a key challenge in the design process is selecting a suitable UHF and IC topology that meets the design requirements while staying within the specified limits. In order to select the initial topology and obtain the appropriate model, the Filter Designer 3D (FD3D) tool for synthesis of resonator VHFs and SCs and diplexers, considering cross-coupling mechanisms, and Filter Designer 2D (FD2D) tool for synthesis of SHFF and SDs of planar type are included in CST STUDIO SUITE. The possibility of extraction of the coupling matrix in FD3D allows efficient configuration of 3D structures of SHFF and SDs.

Characteristics of real SHFF and SD will differ from parameters of their ideal mathematical model due to the influence of material properties, manufacturing inaccuracies, presence of coupling mechanisms and influence of connectors. Numerical modeling in CST STUDIO SUITE allows not only to reveal the mentioned effects, but also to compensate them by optimization means. Combined work of a frequency calculator and powerful optimization algorithms makes it possible to effectively tune necessary combinations of design requirements. The grid partitioning node bias technology will reduce sampling noise, increasing the speed and accuracy of tuning the SHFF and SD, which are extremely sensitive to partitioning configurations.

During operation, losses of electromagnetic energy led to heating and deformation of SHFF and SD. Joint multiphysics modeling connects the results of EM, thermal, and mechanical modeling, allowing the thermal upset of the SHFF and SD to be considered before the working model is fabricated.

A device under development may consist of several parts, the qualitative modeling of which can only be done by different methods. Since the final performance of such complex devices is provided by the interaction of its individual parts, optimizing each part individually may not be sufficient. Optimization of the whole device is required, and the SAM technology provides such an opportunity. When using SAM technology, the device is represented as a schematic diagram consisting of separate elements. In the simplest case, the device can consist of a single parametrized 3D model. The user defines the simulation of this model by describing the analysis tasks. SAM technology makes it possible to compare results obtained with different computational modules or for different variations of the model within the same project. For example, the user can specify related sequences of runs of different calculators: primary electromagnetic analysis of a filter or SD, then its thermal modeling, then its mechanical deformation analysis and final electromagnetic analysis of the filter in order to estimate its detuning. Thus, SAM technology makes it relatively easy to define and perform a complete multiphysics analysis of the device.

By adding other 3D models to the schematic, you can build a complex 3D design. SAM technology tools make it possible to align and match individual parts of the project. Simulations can be defined for one or more parts, and specific analysis methods with their own calculation acceleration settings can be selected for each part. Parts of a device can be described either by their S-parameters or by equivalent field sources for modeling the entire system. The combination of all these methods of modeling at different levels allows to obtain high-quality results and to reduce the requirements on computing resources. Of course, SAM technology allows to define and perform electromagnetic simulation of the whole device.

1.3. Software for modeling planar SHF structures

Currently, the software package Sonnet Suites [6], which is designed for electromagnetic simulation of planar SHF structures: strip and microstrip lines, coplanar waveguides, single- and multi-layer printed circuit boards, including transition holes of various configurations, vertical microstrip lines, as well as antennas, is widely used. A distinctive feature of the Sonnet Suites package is the high simulation accuracy.

The use of the Momentum Method (MoM) in closed volume at its core allows for consistent quality results with an accuracy of 1% or less. Additional program settings allow for repeatable analysis results with an accuracy better than 0.1%. For over 20 years Sonnet has dominated the market for high precision electromagnetic analysis of planar circuits for various applications (RFIC, MMIC) operating in the frequency range from 1 MHz to 2 THz.

Learning high-tech software with a powerful mathematical apparatus inside can generally be a daunting task on its own. Sonnet provides the user with everything they need to learn quickly: an intuitive interface, clear beginner's self-study guides, explanatory user guides, extensive example sets, and thoroughly detailed contextual help.

The flexibility of the Sonnet system makes it possible to embed it in most popular microwave design systems using specially designed interfaces. As a rule, the integration is done at such a high level that no special actions are required from the user, he continues to work in his familiar environment. All data exchange takes place automatically.

Interfaces to the following systems are currently available:

- Cadence Virtuoso;
- Advanced Design System (ADS) by Keysight (Agilent);
- AWR Microwave Office;
- SonnetLab Toolbox for MATLAB, MATCHAD;
- Nuhertz Technologies Filter Solutions;
- Applied Computational Sciences (ACS) LINC2.

The biggest challenge in measuring real SHF devices is feeding the measurement signals to it so that the heterogeneity that occurs in the structure due to the supply line, connector, and probe does not affect its performance. Similarly, high-frequency EM modeling software uses the ports of a circuit to feed signals to its input and measure signal levels at its output. The presence of ports in the EM structure introduces inhomogeneities, the presence of which must then be accounted for by de-embedding techniques, otherwise there will be significant error in the final analysis result.

Sonnet has developed port calibration technology that has proven to be the most accurate in the industry, producing quality S-parameters over a dynamic range of about 100 dB. The unique co-calibrated internal ports are perfectly calibrated connectors that can be used to connect the analyzed structure to any external SHF circuit simulation system operating in the frequency or time domain. These ports can be used to connect to a real topology, such as a nonlinear transistor model. Components can be described by ideal focused models; models provided by component manufacturers; and S-parameter sets derived from measurements of real devices: transistors, amplifiers, discrete elements, etc. Components allow to consider the presence of SMD contact pads and the parasitic effects associated with them.

Sonnet software enables powerful new circuit optimization techniques in which serial or parallel tweaks can be connected to the structure through internal ports at the circuit level.

Sonnet software allows the extraction of equivalent substitution circuits for the analyzed structures, which can then be used in microwave circuit simulation systems using frequency or time methods. The resulting models can include:

- S-, Y- and Z-parameter sets.
- SPICE models based on PI circuits, which are an exact equivalent circuit describing the signal transfer between any two ports, and even considering mutual inductive coupling.
- Wideband SPICE substitution circuits that describe the behavior of an EM structure over a wide frequency range and have no limitations on circuit size and configuration.
- The transversal coupling matrix (TCM) model, which is a matrix for coupled parallel transmission lines.

1.4. Specialized software packages for the design of planar SHF devices

A fundamentally different level of problem complexity is solved by SHF device design systems. As a rule, to obtain the characteristics of bulk structures requires the solution of Maxwell's equations, which is an extremely complex task, which is not always possible to solve in an acceptable form. Therefore, specialized software products have been developed.

1. Optenni Lab software is a specialized 3D and 2D software designed for automatic synthesis of SHF device matching circuits, evaluation of the maximum achievable bandwidth of working frequencies of antennas and calculation of the worst-case decoupling between several antennas in the system. Matching circuits can include both concentrated and distributed elements. Components from a special database can be used as concentrated elements, considering the tolerance for parameter dispersion.

2. EMPro and Momentum

Manufacturer: Agilent Technologies [14, 17, 18, 24, 25].

The main difference between these two software products is that the Momentum package allows the electromagnetic simulation of planar structures only (SHF integrated circuits, high-speed printed circuit boards, SHF modules, antennas), and the EMPro package – full three-dimensional simulation of three-dimensional structures (housings of high-speed and SHF microchips, connecting cables, antennas, on-chip and external passive elements, and PCB interconnections). Key features of the Momentum program:

- combination of full-wave and quasi-static modes of EM modeling of passive SHF elements, interconnections and parasitic effects.
- efficient multi-threaded algorithms reduce simulation time.
- the ability to simulate complex EM effects, including the skin effect and the effect of a substrate, metal conductors of finite thickness and several dielectric layers. Main features of the EMPro program:
- a wide range of modeling technologies. Set up and run analysis using 3D EM simulation technologies in both frequency and time domains: finite element method (FEM) and finite difference time domain method (FDTD).
- user-friendly design interface. Fast creation of arbitrary volumetric structures with a modern, easy-to-use interface; advanced scripting capabilities.

3. Microwave Office

Manufacturer: AWR Corporation [7, 19, 26]. Product website: http://www.awrcorp.com/products/ microwave office.

Intended for modeling planar multilayer structures, modeling of communication systems at the level of structural circuits. Nonlinear analysis is performed by the method of harmonic balance and Volterra series, when a nonlinear circuit is converted into a linear circuit and several "nonlinear current sources". Electromagnetic modeling of planar SHF devices is performed by Galerkin's method of moments. Topology Editor is not just a graphical environment for drawing device topologies, but also a tool for technological preparation for production.

4. CST Microwave Studio [20, 27]

Manufacturer: CST Computer Simulation Technology AG. Product website: http://www.cst.com/Content/ Products/MWS/Overview.aspx.

CST Microwave Studio (CST MWS) is a program designed for fast and accurate numerical simulation of high-frequency devices (antennas, matching devices, filters, power taps, planar and multilayer structures), as well as analysis of signal integrity and electromagnetic compatibility problems in time and frequency domain using rectangular or tetrahedral partition grids [20]. The main advantage of CST computational technologies is the use of approximation for ideal boundary conditions.

Typical devices simulated with the CST Microwave Studio package are:

- waveguide and microstrip directional taps, filtering and matching devices;
- power dividers and totalizers;
- waveguide, microstrip and dielectric filters;
- single- and multilayer microstrip structures;
- various transmission lines;
- coaxial and multi-pin connectors;
- coaxial-waveguide and coaxial-strip junctions;
- optical waveguides and switches;
- different types of antennas – horn, spiral, planar.

Conclusion

From the analysis of the existing mathematical and software design of SHF devices, it follows that modern MO and software allow to design SHF devices for various purposes. At the same time, the developed software uses the methods of modern electrodynamics and the theory of distributed circuits, in particular the theory of transmission lines.

Among the disadvantages inherent in ASP are the following: weak support for analytical operations, limitation of the number of symbolic-analytical operations, non-interactivity of the debugger. Most of the existing methods do not allow (or allow only partially) to control during synthesis the structure and values of SHF circuit elements, which leads to the synthesis of practically non-realizable solutions. The methods of real frequency, systematic search of circuit structures and parametric synthesis are based on nonlinear programming algorithms, so they require a good initial approximation and can lead to unsatisfactory (local-optimal) solutions. Therefore, before using modern ASPs one should obtain, if possible, an approximate solution of the problem that lies in the region of attraction of the global optimal solution (global extremum).

A significant disadvantage of many methods is that they allow solving device synthesis problems only in the "classical" formulation, when the requirements are made to the frequency response of the circuit power transfer. However, in practice, we often encounter another formulation of the synthesis problem: a corrective (CC) or matching (MC) circuit is a part of a device or some power transmission system, and it is usually necessary to ensure the specified requirements to the set of characteristics of this device or systems. For example, when designing wideband SHF amplifier stages with reactive MCs, these circuits must have not only the necessary frequency dependence of the transmit power, but also a given impedance (input or output) to meet the requirements for stability, noise figure, output power, etc. Due to the noted disadvantages, a significant place in the design of wideband CCs and MCs is still occupied by the heuristic approach. Its essence is that the structure of a CC (MC) is chosen by the designer himself based on his own experience, simplified approximate methods of calculation (synthesis), the Wolpert-Smith diagram, etc., and finally the circuit parameters are determined by means of parametric optimization methods. Unfortunately, this approach leads to non-optimal solutions, is labor-intensive, and imposes high requirements for the designer's qualification. Thus, the design process of wideband CCs and MCs included in the SHF REU, considering the requirements to the characteristics of REU, the structure and parameters of the synthesized circuit is still a complex problem. To solve it requires the development of appropriate methods and algorithms for computer-aided design of CCs and MCs, as well as specialized software products. The important place of the problem of synthesis of CC and MC takes at designing of wideband microwave transistor amplifiers. In this case, it is necessary to synthesize reactive four-pole SC, as well as two-pole correction or feedback circuits (FC), based on the set of requirements for the characteristics of the amplifier. In the presence of the above disadvantages, typical for the existing methods of synthesis of CC and MC the design of microwave amplifiers also becomes difficult and leads to suboptimal solutions. At present on the software market there are several specialized products that solve the problem of CC and MC synthesis (MultiMatcli, Genesys, Smith, ZMatch, RF Compiler), as well as microwave transistor amplifiers (MultiMatch, Linc2, RF Compiler). The most developed program, which allows to synthesize CC and MC is MultiMatch. Despite a wide enough practical application, it has several disadvantages. It does not provide full control of the synthesized circuit structure and uses deterministic search methods, which leads to local-optimal solutions. The procedure of designing SHF transistor amplifiers with this program is multistage and complex, which imposes high requirements to the qualification and training of the developer. The other programs have disadvantages of the methods used in them: do not allow broadband matching (Smith), do not provide the ability to control the values of elements and circuit structure during synthesis (Genesys, ZMatch), require a high level of user training (Smith, Linc2), contain non-linear programming procedures (ZMatch, RF Compiler).

Passive elements of SHF circuits are sections of transmission lines of different structures, components with concentrated parameters, dielectric resonators, non-reciprocal devices and planar (two-dimensional) elements. Coaxial lines, waveguides, strip, microstrip, coplanar, slot lines or combinations of these lines can be used as transmission lines. Modeling difficulties limit the use of SHF computer-aided design techniques. Detailed modeling of active devices, is a very difficult task, taking considerable time. Therefore, there is a need to simplify equivalent circuits and obtain expressions in closed form, the accuracy of which is sufficient for design. These expressions for microstrip, slot and coplanar lines, as well as for inhomogeneities in microstrip lines are contained in the book [2].

As world practice has shown, the successful creation of SHF integrated devices is associated not only with complex technological problems, but also with solving no fewer complex problems of MIC (monolithic integrated circuits) design, development of appropriate software. In particular, the most important problem facing the developer is the accurate modeling of microwave devices in each frequency range. For this purpose, modern software tools for automated design of SHF devices are used, such as Microwave Office (Applied Wave Research, USA), ADS (Agilent Technologies, USA), Serenade (Ansoft Corp., USA), Genesys (Eagleware Corp., USA), etc. However, to solve the problem of designing high-quality monolithic SHF devices based on domestic technology the availability of these programs is not enough, because the element models available in them are not tied to a specific technology. Successful design of SHF devices is possible only with the creation of libraries of topological and electrical models of MIC elements, reflecting the specific technology of the manufacturer, and the integration of these libraries in common systems for modeling SHF devices. It should be noted that foreign firms – software developers in cooperation with companies – manufacturers (technology developers) of SHF MIC purposefully conduct such work and create such libraries. However, during the development and implementation of new microwave MIC manufacturing technologies (monolithic integrated circuits) such libraries need to be created anew.

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Німич О., Клобукова Л., Нестеренко К., Яковів І.
ОГЛЯД МАТЕМАТИЧНОГО ТА ПРОГРАМНОГО ЗАБЕЗПЕЧЕННЯ ПРОЕКТУВАННЯ ПРИСТРОЇВ НВЧ

Сьогодні під час розроблення пристроїв НВЧ широко використовують машинні методи проектування, які базуються на наявних базах знань і базах даних. Розвиток обчислювальної техніки дозволив на основі ЕОМ проектувати різні складні розподілені системи, які класичними аналітичними методами здійснити неможливо. Відомі результати з дослідження різних пристроїв НВЧ та їхньої елементної бази подано у вигляді баз даних різних предметних галузей. Зростання швидкості передавання інформації призвело до необхідності розроблення нових підходів до розроблення математичного (МЗ) і програмного (ПЗ) забезпечення. При цьому основною проблемою є відсутність універсального МЗ і ПЗ, що дає змогу порівняно просто розв'язувати широкий клас задач проектування різних НВЧ пристроїв.

Вибір відповідного ПЗ є досить складною проблемою і залежить від досвіду і кваліфікації розробників. Зазвичай під час вибору ПЗ розробники звертаються до різних вузькоспеціалізованих експертів, які досить часто також не в змозі дати аргументовані поради. Тому виокремлення потрібного класу ППП для проектування НВЧ пристроїв із великого розмаїття наявних пакетів є актуальним завданням.

Аналіз останніх публікацій показав, що під час проектування пристроїв НВЧ нині використовують сотні різних ППП, розроблені на основі різних підходів до розроблення моделей і методів їхнього аналізу. Ця обставина не дає змоги порівняно швидко вибрати відповідні ППП. Крім того, під час розв'язання задач проектування різними методами часто кінцеві результати відрізняються один від одного. Тобто, кінцевий результат залежить від використовуваного ППП. Таким чином, для отримання найкращого результату іноді потрібне розв'язання однієї і тієї ж задачі різними методами. І після цього здійснюється вибір найкращого результату. Така процедура вимагає великих економічних витрат і не гарантує отримання найкращого результату.

Мета статті *- ознайомлення спеціалістів з проектування різних пристроїв НВЧ із математичним та програмним забезпеченням автоматизованого проектування, найбільш прийнятних для розробки розподілених систем.*

*У статті здійснено аналітичний огляд сучасного математичного забезпечення автоматизованого проектування систем НВЧ у форматах **1D**, **2D**, **3D** моделювання.*

Ключові слова: математичне забезпечення; програмне забезпечення; база даних, пристрої НВЧ; автоматизоване проектування; лінії передавання; планарні пристрої.

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REVIEW OF MATHEMATICAL SUPPORT AND SOFTWARE FOR DESIGN OF SHF DEVICES

Currently, machine design methods are widely used in the development of super high frequency devices (SHF), which are based on existing knowledge bases and databases. The development of computer technology has allowed based on computers to design various complex distributed systems, which by classical analytical methods are impossible to implement. Known results on the study of various SHF devices and their element base are presented in the *form of databases of various subject areas. Growth in the rate of information transfer has led to the need to develop new approaches to the development of mathematical support (MS) and software. At the same time, the main problem is the lack of universal MS and software, which allows to solve a wide class of problems of designing various SHF devices relatively easily.*

The choice of suitable software is quite a complex problem and depends on the experience and qualifications of the developers. As a rule, when selecting software, developers turn to various highly specialized experts, who quite often are also unable to give reasoned advice. Therefore, the selection of the required class of software for SHF device design from the large variety of existing packages is an important task.

Analysis of recent publications has shown that the design of SHF devices currently uses hundreds of different ASPs, developed based on different approaches to the development of models and methods of their analysis. This circumstance does not allow us to choose the appropriate ASP relatively quickly. In addition, when solving the design problems by different methods, often the results differ from each other. That is, the result depends on the used ASP. Thus, to get the best result sometimes it is required to solve the same problem by different methods. And after that the choice of the best result is made. Such a procedure requires high economic costs and does not guarantee the best results.

***The purpose of the article** is to acquaint SHF device designers with the mathematical and computer-aided design software most suitable for the development of distributed systems.*

*The article provides an analytical review of modern mathematical support and software for computer-aided design of SHF systems in **1D**, **2D**, **3D** modeling formats.*

Keywords: mathematical software; software; database, SHF devices; computer-aided design; transmission lines; planar devices.

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