

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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INVESTIGATION OF FREQUENCY PROPERTIES OF HELICAL AND MEANDER SLOW-WAVE SYSTEMS

SUMMARY OF DOCTORAL DISSERTATION

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Introduction

Topicality of the problem

Helical and meander slow-wave systems are widely used in modern electronic systems and devices: antennas, filters, hubs, monolithic integrated circuits, high speed digital data transfer devices.

In the middle of the twentieth century slow-wave systems were designed using experimental and analytical methods. With the development of computer technologies and the limitations of the analytical methods became more evident, numerical methods have been widely applied. Simulation of microwave devices using numerical methods is complicated because of computing time is relatively long even using a powerful workstations. From the middle nineties of the twentieth century a new technology was introduced. It allowed the distribution of tasks between personal computers or graphical and specialized purpose microprocessors, enabling the parallel computation. Artificial neural network techniques have been recognized as a useful alternative to conventional simulation methods of microwave devices in recent years.

Due to periodic inhomogeneities and multiple reflections from them slow-wave systems are gaining undesirable features of stop-band filters. Because of this reason, the dispersion of retardation factor increases and the working frequency range of slow-wave system and the entire microwave device becomes narrower. In order to extend the working frequency range and reduce the dispersion of retardation factor it is appropriate to search for the new constructions of slow-wave systems.

It is relevant to search for new automated investigation methods of slow-wave systems using artificial neural networks in order to find parameters of slow-wave systems avoiding the complex mathematical models and to accelerate the process of investigation without additional expensive equipment.

The problem of the improvement of the modeling techniques of slow-wave systems and the research of improved design of slow-wave systems with periodical inhomogeneities are investigated in the dissertation.

Object of research

Objects of research – models of slow-wave systems with periodical inhomogeneities and their methods of investigation.

Aim of the work

The aim of the work is to improve analysis techniques and models of inhomogeneous slow-wave systems in order to reveal the common properties

and possibilities of automation of modelling process of helical and meander slow-wave systems containing periodical inhomogeneities.

Tasks of the work

To achieve the aim of the work the following tasks must be solved:

1. Investigate the influence of periodic inhomogeneities to the properties of inhomogeneous slow-wave systems.
2. Investigate properties of helical, meander and hybrid slow-wave systems with periodic inhomogeneities.
3. Create an automated computer added analysis and synthesis algorithms for calculation of characteristics of slow-wave systems with periodic inhomogeneities using artificial neural networks.
4. Validate the efficiency of proposed methods using imitational calculations.

Methodology of research

The work applies methods of electrodynamic problem solution adapted for analysis of slow-wave systems – matrix, transmission and multiconductor lines, numerical methods and artificial neural network theory. Computer models of slow-wave systems and developed algorithms are implemented using Matlab[®] and specialized CST Microwave Studio[®] and Sonnet[®] software packages.

Scientific novelty

The following results, significant to science of electrical engineering were obtained:

1. New models and new methods for investigation of stop-band filter properties of inhomogeneous wideband periodic slow-wave systems are developed as well as their results are obtained.
2. Algorithms are designed to explore the influence of parameters of slow-wave systems to the width of the stop-band and their results are used to design helical slow-wave systems.
3. Mathematical models of helical, meander and hybrid slow-wave systems are created and their dispersion equations are derived, which allow to reveal the influence of periodical inhomogeneities and transverse asymmetry to frequency characteristics of slow-wave systems.
4. Calculation methodology of frequency characteristics of inhomogeneous slow-wave systems is developed using artificial neural networks in order to determine frequency characteristics without derivation of systems dispersion equations. Automated computer-aided design algorithms for slow-wave systems are created relying on artificial neural networks.

Practical value

Methods and iterative computation algorithms which evaluate periodical inhomogeneities and reveal properties of latest constructions of slow-wave systems are created. Automated computer-aided design algorithms for computing frequency characteristics of slow-wave systems, which allow to refuse sophisticated analytical methods, are created by using artificial neural networks. Software that allows to design and analyze models of inhomogeneous periodical slow-wave systems is created using Matlab[®] software package.

Defended propositions

1. Due to periodical inhomogeneities and multiple reflections from them, slow-wave systems obtain properties of the stop-band filters. Stop-band appears when the phase angle between the voltages or currents on the neighbour conductors approach to $\pi/2$ or π .

2. Dispersion properties of slow-wave systems containing periodical inhomogeneities can be improved and stop-band can be reduced by reducing the factor of characteristic impedances along the conductor to 1.3, by increasing the factor of lengths of homogeneous sections to 1.5 and by reducing the period of inhomogeneities.

3. The retardation factor, the input impedance and the sensitivity of the meander slow-wave system can be considerably increased by using hybrid slow-wave system which consists of meander conductors in the central part and helical turns in the peripheral parts of the system.

4. Algorithms based on artificial neural networks allow the use of computer-aided design and analysis methods of inhomogeneous slow-wave systems without derivation of dispersion equations.

The scope of the scientific work

The dissertation consists of an introduction, four chapters and a summary. There are also two appendixes.

The total scope of the dissertation – 116 pages, not including appendixes, 73 numbered formulae are used in the text, 60 pictures and 3 tables. Bibliography consist of 128 literature sources.

1. Review of Inhomogeneous Slow-Wave Systems and Their Methods of Analysis

Models and properties of periodical inhomogeneous slow-wave systems are reviewed in the first chapter. Applications of slow-wave systems containing periodical inhomogeneities are discussed. Methods applied in the investigation

of inhomogeneous periodical slow-wave systems are described. Problems which arise from the applications of slow-wave systems are also reviewed. Possibilities to use artificial neural network in investigation of slow-wave systems are discussed.

The study is focused on slow-wave systems. The main goal of analysis of the slow-wave systems is to determine its frequency characteristics – the retardation factor and characteristic impedance versus frequency.

The retardation factor k_R shows how many times the phase velocity v_{ph} in the slow-wave system is less than light velocity c_0 in vacuum. According to transmission line theory

$$k_R = c_0/v_{ph} = c_0\sqrt{L_1C_1}, \quad (1)$$

where L_1 and C_1 are inductance and capacitance per unit length.

Characteristic impedance of the system can be found using the equation:

$$Z_C = \sqrt{L_1/C_1} = \underline{U}(x)/\underline{I}(x), \quad (2)$$

where $\underline{U}(x)$ and $\underline{I}(x)$ are voltage and current at the section of the system with coordinate x .

Researches of slow-wave systems are relevant. Helical and meander slow-wave systems are widely used in modern electronic systems and devices: antennas, filters, hubs, monolithic integrated circuits, high-speed digital data transfer devices.

The retardation factor, characteristic impedance, input impedance and other characteristics of slow-wave systems are determined as a result of the solution of the dispersion equation. In the case of the complex inhomogeneous slow-wave structures, derivation of the dispersion equation is complicated. Real slow-wave systems are inhomogeneous systems. Numerical methods allow to avoid many difficulties, arising from the analytical iterative calculations, but simulation of slow-wave systems using numerical methods is also complicated, because computing time is relatively long even using a powerful workstation. In recent years, artificial neural network techniques have been recognized as a useful alternative to conventional slow-wave systems simulation methods.

Possibilities to improve automated simulation process using the method based on artificial neural networks and avoid some modelling problems which arise from the iterative calculations are discussed in this dissertation.

Due to periodic inhomogeneities and multiple reflections from them slow-wave systems are gaining undesirable features of stop-band filters. In order to extend the working frequency range and reduce the dispersion of retardation

factor it is appropriate to search for the new constructions of slow-wave systems.

Helical and meander slow-wave systems are investigated by prof habil dr S. Štaras, R. Kirvaitis, R. Martavičius, J. Skudutis, Prof dr V. Urbanavičius, associated professor dr. V. Daškevičius and others. Slow-wave system intensively investigated from the seventh decade of the twentieth century. S. Štaras investigated helical and meander structures of slow-wave systems. R. Martavičius considered broadband planar slow-wave systems. V. Urbanavičius investigated microstrip delay lines using numerical methods. J. Skudutis and V. Daškevičius applied the specialized software for investigation of helical and meander structures of slow-wave systems. R. Kirvaitis investigated electrodynamic properties of delay lines.

The above mentioned researchers noticed that in some cases helical and meander slow-wave systems are affected by resonances. The author of this dissertation investigates the resonant effects of helical and meander slow-wave systems, which leads to the dispersion of frequency characteristics and formation of the stop-band. Author applies artificial neural networks for automated computer-aided analysis and design of helical and meander slow-wave systems.

2. Investigation of Properties of Inhomogeneous Periodical Systems

Properties of transmission line containing periodical inhomogeneities are considered in the second chapter. General properties of structures containing periodical inhomogeneities are revealed by using model of the transmission line. The transmission line with periodically changing characteristic impedance can be used as the simplest model for simulation of influence of finite number of inhomogeneous periods to wave propagation (Fig. 1).

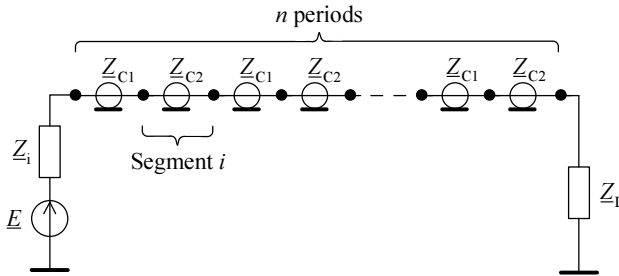


Fig. 1. The scheme of the signal tract with the transmission line containing periodical inhomogeneities

The line consists of n periods. A period consists of two segments with lengths l_1, l_2 and characteristic impedances $\underline{Z}_{C1}$ and $\underline{Z}_{C2}$. The line is connected to the signal source $\underline{E}$ with internal impedance $\underline{Z}_i$ and loaded with load resistance $\underline{Z}_L$.

Input impedance and transfer function characterize the properties of the line. Input impedance can be found using equation:

$$\underline{Z}_{\text{IN}i} = R_{\text{IN}i} + jX_{\text{IN}i} = \underline{Z}_{Ci} \frac{\underline{Z}_{Li} + j \cdot \underline{Z}_{Ci} \cdot \tan(\beta_i l_i)}{\underline{Z}_{Ci} + j \cdot \underline{Z}_{Li} \cdot \tan(\beta_i l_i)}, \quad (3)$$

where index i describes the number of the segment of the line; $\underline{Z}_{\text{IN}i}$, $\underline{Z}_{Ci}$, $\underline{Z}_{Li}$ are input, characteristic and load impedances respectively; β_i is phase coefficient; l_i is the length of the segment.

The **ABCD** matrix method can be used for calculations of transfer coefficient of amplitude frequency responses of inhomogeneous periodical structures. Every single homogeneous section is treated as a separate four-port with parameters of **ABCD** matrix. **ABCD** matrices are connected in cascade until the equivalent four-port of whole transmission line is obtained (Fig. 2).

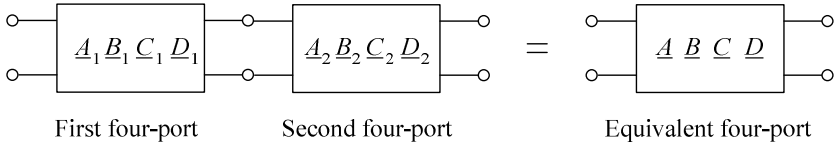


Fig. 2. Cascaded circuit of four-ports

Values of the normalized amplitude-frequency response are given by

$$\underline{K}(f) = K(f) e^{-j\phi(f)} = \frac{R_i + R_L}{R_L} \frac{\underline{U}_o}{\underline{E}}. \quad (4)$$

According to calculations, increase of number n of inhomogeneous periods of the line causes increase of variation and non-uniformity of input impedance and transfer coefficient. For instance, frequency characteristics of the line at $\underline{Z}_{C1}/\underline{Z}_{C2} = 1.5$, $n=4$ and different factor of l_1/l_2 are presented in Figure 3. Variation of input impedance and transfer coefficient increases and the stop-band appears when ratio l_1/l_2 approaches to 1.

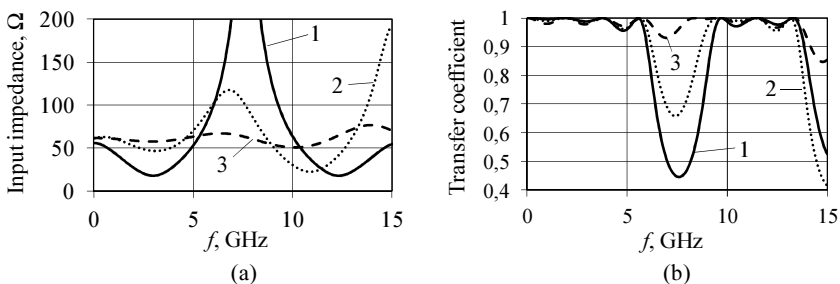


Fig. 3. Input impedance (a) and transfer coefficient (b) characteristics of the inhomogeneous electromagnetic transmission line at $R_L = R_i = 50 \Omega$ and: $Z_{C1} = 40 \Omega$, $Z_{C2} = 60 \Omega$, $n = 4$ and l_1/l_2 equal to: 1 – 2; 2 – 4; 3 – 19

According to other calculations, attenuation in the stop-band depends on magnitude of inhomogeneities (values of Z_{C1}/Z_{C2} and l_1/l_2) and number n of inhomogeneous periods. It increases with increase of Z_{C1}/Z_{C2} and n and decrease of ratio l_1/l_2 . The width of the stop-band practically does not depend on the number of inhomogeneous periods when it is greater than 4.

3. Investigation of Properties of Slow-Wave Systems

The theory of slow-wave systems and multiconductor lines method can be used for modeling and analysis of the infinitely long structures containing periodical inhomogeneities. Conductors of helical and meander slow-wave systems are presented in Figure 4.

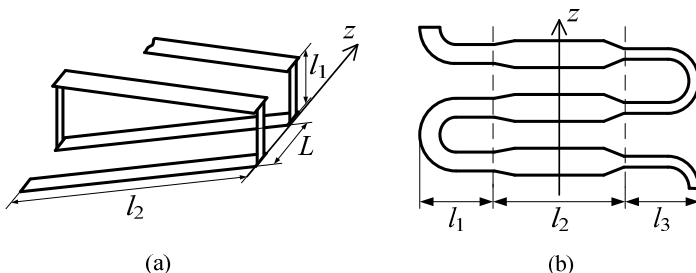


Fig. 4. The view of the helical conductor (a) and the view of the meander conductor (b) of slow-wave systems

The number of homogeneous sections in the inhomogeneous period, dimensions of the helical and meander conductors and the gaps between the conductors and their shields can be different in the sections. The model of multiconductor lines of helical slow-wave system containing two homogeneous sections along the helix is presented in Figure 5. The following expressions for voltages and currents in the conductor of the multiconductor line are used:

$$\underline{U}_{in}(x) = (\underline{A}_{i1} \sin kx + \underline{A}_{i2} \cos kx) e^{-jn\theta}, \quad (5)$$

$$\underline{I}_{in}(x) = jY_i(\theta) (\underline{A}_{i1} \cos kx - \underline{A}_{i2} \sin kx) e^{-jn\theta}, \quad (6)$$

where $\underline{A}_{in}$ – coefficients; i – the number of the segment of the multiconductor line; n – the number of the conductor in the row; k – the wave number; θ – the phase angle between the voltages or currents on the adjacent conductors; $Y_i(\theta)$ – the characteristic admittance of the segment i .

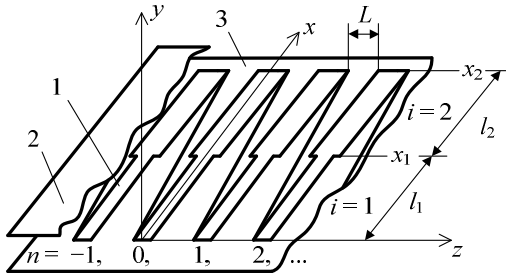


Fig. 5. The model of the helical line: 1 – conductor of the multiconductor line; 2, 3 – shields

Once boundary conditions are satisfied, values of the k , corresponding to the given θ can be found, using principles of the matrix algebra and iterations. Values of retardation factor k_r and input impedance $Z_{IN}(x)$ can be found:

$$k_r = c_0 / v_{ph} = \theta / kL, \quad (7)$$

$$Z_{IN}(x) = \underline{U}(x) / \underline{I}(x), \quad (8)$$

where v_{ph} – the phase velocity of the travelling-wave, L – the step between conductors of the multiconductor line in the model of the system.

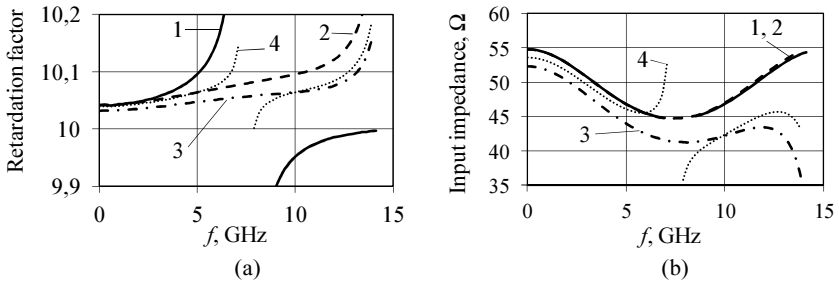


Fig. 6. Retardation factor (a) and input impedance (b) versus frequency of helical slow-wave system at $x_2 = l_1 + l_2 = 20$ mm, $L = 2$ mm and:

- 1 – $l_1 = l_2 = 10$ mm, $Z_1(0)/Z_1(\pi) = 60/40 \Omega$, $Z_2(0)/Z_2(\pi) = 60/40 \Omega$;
- 2 – $l_1 = l_2 = 10$ mm, $Z_1(0)/Z_1(\pi) = 60/40 \Omega$, $Z_2(0)/Z_2(\pi) = 50/40 \Omega$;
- 3 – $l_1 = l_2 = 10$ mm, $Z_1(0)/Z_1(\pi) = 70/40 \Omega$, $Z_2(0)/Z_2(\pi) = 50/40 \Omega$;
- 4 – $l_1/l_2 = 5/15$ mm, $Z_1(0)/Z_1(\pi) = 60/40 \Omega$, $Z_2(0)/Z_2(\pi) = 50/40 \Omega$

Figure 6 illustrates how retardation factor k_r and input impedance Z_{IN} of the helical system containing two homogeneous segments depend on the ratio of characteristic impedances $Z_i(\pi)$ and lengths of homogeneous segments in the period at $Z_i(0) = \text{const}$.

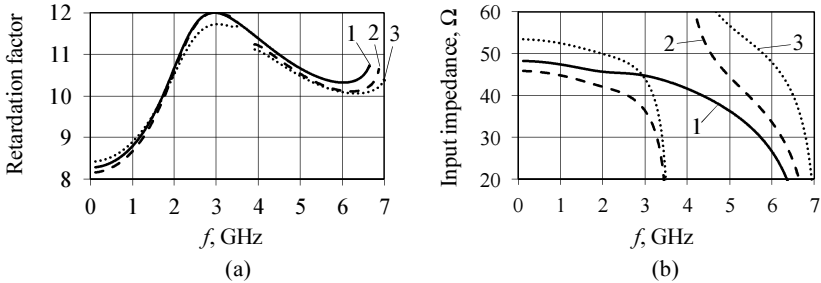


Fig. 7. Retardation factor (a) and input impedance (b) versus frequency of meander slow-wave system with transverse asymmetry at $x_3 = l_1 + l_2 + l_3 = 20$ mm, $L = 2$ mm and:

- 1 – $Z_1(0)/Z_1(\pi) = 70/50 \Omega$, $Z_2(0)/Z_2(\pi) = 50/30 \Omega$, $Z_3(0)/Z_3(\pi) = 70/50 \Omega$;
 $l_1 = 5$ mm, $l_2 = 10$ mm, $l_3 = 5$ mm;
- 2 – $Z_1(0)/Z_1(\pi) = 70/50 \Omega$, $Z_2(0)/Z_2(\pi) = 50/30 \Omega$, $Z_3(0)/Z_3(\pi) = 60/40 \Omega$;
 $l_1 = 5$ mm, $l_2 = 10$ mm, $l_3 = 5$ mm;
- 3 – $Z_1(0)/Z_1(\pi) = 70/50 \Omega$, $Z_2(0)/Z_2(\pi) = 50/30 \Omega$, $Z_3(0)/Z_3(\pi) = 70/50 \Omega$;
 $l_1 = 5$ mm, $l_2 = 5$ mm, $l_3 = 10$ mm

At $Z_i(0) = \text{const}$, periodical variation of characteristic impedance $Z_i(\theta)$ along the helix turn causes increase of retardation factor. If $Z_i(0) = \text{const}$, we can reduce dispersion of retardation factor and input impedance decreasing variation of characteristic impedance $Z_i(\pi)$ and shortening the section with less length. The input impedance of the helical system containing periodical inhomogeneities strongly depends on coordinate x and ratio of lengths of homogeneous sections (Fig. 6 b).

In traveling-wave deflection systems meander electrodes containing wide central parts of meander conductors and narrowed peripheral parts are used (Fig. 4 b). The influence of asymmetrical inhomogeneities on properties of meander slow-wave systems are presented in Figure 7. Curves 2 are obtained at different peripheral parts of meander system, curves 3 – at shifted central part of meander electrode. Asymmetry of the system causes radical changes of its frequency properties. At asymmetry, input impedance rapidly changes when phase angle θ approaches to $\pi/2$. As a result, discontinuity of frequency characteristics and the stop-band appear at two times smaller frequencies.

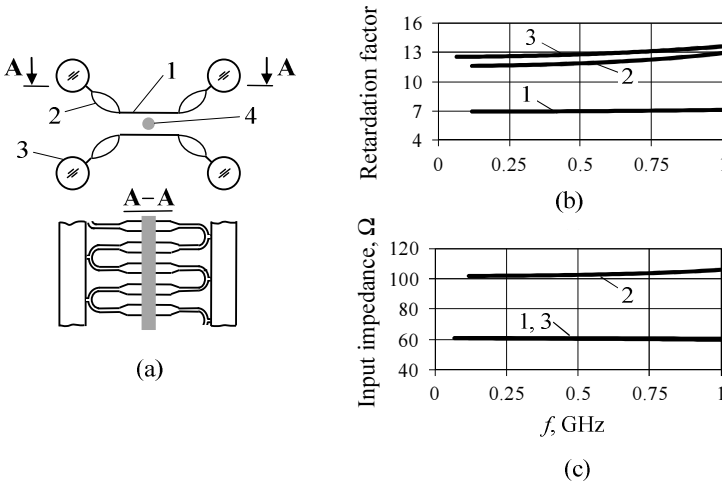


Fig. 8. The cross-section and top view of the hybrid slow-wave system where 1 – central part; 2 – formed peripheral parts; 3 – dielectric holder; 4 – electron beam (a) and retardation factor (b) and input impedance (c) of the hybrid system versus frequency at $L = 2$ mm, thickness of conductors 0.2 mm, gaps between them in the central part 0.5 mm, shield distances 0.5 and 10 mm, characteristic impedances $Z(0) = 87.7 \Omega$, $Z(\pi) = 42.6 \Omega$ and: 1 – $a = 10$ mm, $LH = 0$ nH; 2 – $a = 10$ mm, $L_{ind} = 5$ nH, 3 – $a = 18$ mm, $LH = 0$ nH

Characteristics of the hybrid structure (Fig. 8 a), which were calculated using the multiconductor lines method, are presented in Figure 8 (b) and (c). According to them, using meander electrodes with formed lateral parts, retardation factor and input impedance of the slow-wave system can be increased 1.7 times. This may lead to desirable increased sensitivity of the slow-wave deflection system.

The adequacy of designed mathematical modules of helical, meander and hybrid slow-wave systems and developed algorithms for analysis of slow-wave systems were verified by numerical moments and finite difference time domain methods using CST Microwave Studio® and Sonnet® software packages.

4. Investigation and Design of the Slow-Wave Systems Using Artificial Neural Networks

Usually analytical iterative calculations are used to investigate the parameters of slow-wave systems. A simulation using analytical iterative calculations is a time consuming operation. This is a problem, when it is necessary to repeat calculations many times with different input parameters. Moreover, iterative calculations are faced with problems when it is necessary to determinate ambiguous solutions in calculations of the root of dispersion equation. Artificial neural networks (ANN) techniques have been recognised as useful alternatives to conventional approaches in microwave modelling in recent years.

It is proposed a new on ANN based algorithm, which allows to avoid difficulties of analytical iterative methods and improve investigation process of slow-wave systems, in the dissertation. Radial basis function (RBF) network is used in order to increase the training data arrays. Multilayer perceptron (MLP) network is used in the tasks of analysis and synthesis of slow-wave systems.

The structure of MLP depends on the complexity of the problem (Fig. 9). In this case, the input layer consisted of seven neurons, the output layer consisted of six neurons and hidden layer consisted of 28 neurons. The number of neurons in the hidden layer was selected during the experiment. The activation function of neurons in the hidden layer is hyperbolic tangent sigmoid. Neurons of the output layer use linear activation function. The applied back propagation learning algorithm, which is optimized for embedded systems.

Presented algorithm (Algorithm 1) is suitable for both helical and meander slow-wave systems. Results of simulation of helical slow-wave system using multilayer perceptron network are presented in Figure 10. Results, obtained by using MLP, are similar to the results, obtained using iterative calculations.

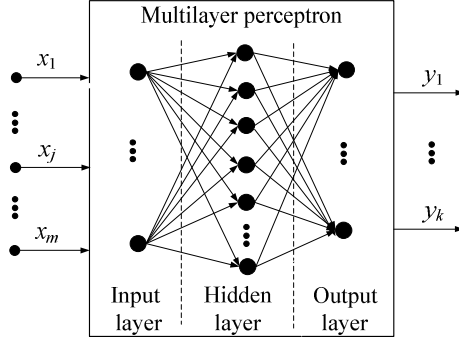


Fig. 9. The multilayer perceptron, used for the modelling of slow-wave systems

On the other hand, divergences of the results obtained using ANN varies from 5 to 15 percent, comparing with results obtained with iterative analytical multiconductor lines method. Divergences varies as neural network has more difficulties in interpreting values of analyzed edge areas of frequency characteristics and areas where frequency characteristics are rapidly changing.

It is difficult to interpret break points in frequencies characteristics of slow-wave systems with multilayer perceptron network, therefore multilayer perceptron network is trained to determine cut-off frequencies of the pass band and the calculations are performed for each of the pass band separately.

It is important to note that intermediate point's approximation using RBF took approximately 0.16 seconds with every data sample, when the number of examples was 7x60. The general data approximation time using RBF was 1.34 seconds. The learning process of the MLP took about 14 minutes.

Algorithm 1. Sequence of analysis actions of slow-wave systems

- A. Collecting samples for RBF network training.
 - Retardation factor k_R and input impedance Z_{IN} dependence on f .
 - B. RBF network simulation.
 - C. MLP training.
 - Collection of k_R , Z_{IN} and cut-off frequencies of the pass bands characteristics dependences on the frequency, lengths and characteristic impedances of the homogeneous segments.
 - D. Simulation of MLP.
 - Simulation of k_R , Z_{IN} and cut-off frequencies characteristics dependences on the frequency, lengths and characteristic impedances of homogeneous segments.
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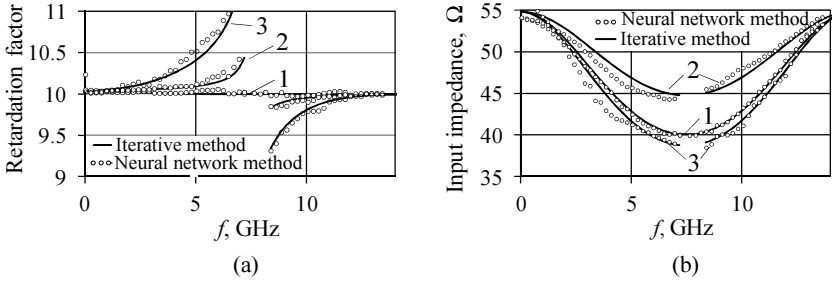


Fig. 10. Retardation factor (a) and input impedance (b) versus frequency of helical slow-wave system at $l_1 + l_2 = 20$ mm, $l_1 = l_2 = 10$, $L = 2$ mm and:

- 1 – $Z_1(0) = 60 \Omega$, $Z_1(\pi) = 40 \Omega$, $Z_2(0) = 50 \Omega$, $Z_2(\pi) = 40 \Omega$;
- 2 – $Z_1(0) = 60 \Omega$, $Z_1(\pi) = 50 \Omega$, $Z_2(0) = 50 \Omega$, $Z_2(\pi) = 40 \Omega$;
- 3 – $Z_1(0) = 60 \Omega$, $Z_1(\pi) = 50 \Omega$, $Z_2(0) = 50 \Omega$, $Z_2(\pi) = 30 \Omega$

Finally, the calculations using the MLP took 0.01 seconds in the last stage of investigation, when the similar calculations using iterative method took 4.65 seconds. Therefore the analysis process of helical slow-wave system took 465 times faster. Similar results were obtained by solving analysis tasks of meander slow-wave system.

Comparison of initial sets of electrical parameters of the helical slow-wave system and results of parametric synthesis obtained using multilayer perceptron network are sufficiently accurate (Table 1). Variation of results does not exceed 8 percent error from the standard. The standard was considered as results obtained by solving analysis problem using analytical iterative calculation methods when looking for electrical parameters after selecting a specific set of geometrical and physical parameters.

Table 1. Parametric synthesis results of the helical slow-wave system

Variant	$l_1 = l_2$, mm	$Z_1(0)$, Ω	$Z_1(\pi)$, Ω	$Z_2(0)$, Ω	$Z_2(\pi)$, Ω
Standard	10	60	40	60	40
1	10	62.1	41.2	61.7	40.8
Standard	10	60	50	50	40
2	10	63.5	54	55.2	38.3
Standard	10	60	50	50	30
3	10	60.8	52.6	49.4	33.4

The learning process of the multilayer perceptron network took about 50 seconds. Calculations took approximately 0.01 seconds using the multilayer

perceptron network. Calculations were performed by medium-power PC using MATLAB[®] programming package.

There was confirmed that artificial neural networks are suitable for automated design of helical and meander slow-wave systems in the fourth chapter.

General Conclusions

After designing mathematical models of helical, meander and hybrid slow-wave systems, as well as after performing computer experiments according to these models and after verifying results with the results obtained with specialized software packages, the following scientific conclusions were formulated:

1. It is possible to investigate resonant phenomena, their reasons and impact on stop-band filter properties and frequency characteristics of helical and meander slow-wave systems using mathematical models of transmission and multiconductor lines by applying matrix, transmission and multiconductor lines methods. The adequacy of the research results of the investigated models was proved by using specialized CST Microwave Studio[®] and Sonnet[®] software packages, which perform by the finite-difference time-domain and moment methods.

2. Investigations have shown that due to periodical inhomogeneities and multiple reflections from them slow-wave systems obtain properties of the stop-band filters then phase angle between voltages or currents in adjacent conductors approach to $\pi/2$ or π . Dispersion properties can be improved and stop-band can be reduced of the slow-wave systems containing periodical inhomogeneities by reducing the factor of characteristic impedances along the conductor to 1.3, by increasing the factor of lengths of homogeneous sections to 1.5 and by reducing the period of inhomogeneities.

3. Investigations have shown that by increasing the sensitivity of the electrical device which has a slow-wave deflection system and by using meander electrodes with a wide central conductor and narrowed peripheral conductors it is important to avoid the transverse asymmetry of meander conductor, which two times narrows the pass-band width of the device.

4. The input impedance and the retardation factor are managed to increase by 1.7 times by using the hybrid slow-wave system which peripheral areas of the meander conductor are replaced by helix coils.

5. Based on artificial neural networks computer-aided design algorithms for slow-wave systems with periodic inhomogeneities allow to accelerate the synthesis and analysis tasks of investigated helical, meander and hybrid slow-

wave systems in 465 times and avoid the derivation of dispersion equations. Divergences of the analysis results obtained by using artificial neural network do not exceed 15 % comparing with results obtained by standard multiconductor lines method. Divergences of parametric synthesis results do not exceed 8 % from the standard.

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SPIRALINIŲ IR MEANDRINIŲ LĖTINIMO SISTEMŲ DAŽNINIŲ SAVYBIŲ TYRIMAS

Mokslo problemos aktualumas

Spiralinės ir meandrinės konstrukcijos lėtinimo sistemos plačiai naudojamos šiuolaikinėse elektroninėse sistemose ir įtaisuose: antenose, filtruose, šakotuvuose, monolitiniuose integrinuose grandynuose, didelio duomenų perdavimo greičio skaitmeniniuose įtaisuose ir pan.

XX a. viduryje lėtinimo sistemos buvo projektuojamos taikant eksperimentinius ir analitinius metodus. Vystantis kompiuterinei technikai ir išryškėjus analitinių metodų apribojimams dėl sudėtingo matematinio modelio aprašymo plačiau pradėti taikyti skaitiniai metodai. Taikant skaitinius metodus skaičiavimai analizuojant praktikoje taikomus įtaisus gali trukti daug valandų net naudojant pajėgias darbo stotis. Nuo XX a. dešimto dešimtmečio vidurio taikomos technologijos, leidžiančios išlygiagretinti skaičiavimus tarp asmeninių kompiuterių arba grafinių bei specialios paskirties mikroprocesorių. Pastaraisiais metais dirbtinių neuronų tinklų metodai buvo pripažinti kaip naudinga alternatyva tradiciniams mikrobangų modeliavimo metodams.

Spiralinės ir meandrinės lėtinimo sistemų konstrukcijos dėl periodiškai kintančių vienalyčių sričių ir nuo jų susidarančių atspindžių įgauna nepageidaujamas užtvarinių filtrų savybes. Dėl šios priežasties didėja lėtinimo

koeficiento dažninių charakteristikų dispersija ir siaurėja lėtinimo sistemos ir viso elektrodinaminio įtaiso darbo dažnių juostos plotis. Todėl tikslinga ieškoti naujų lėtinimo sistemų konstrukcijų, leisiančių praplėsti darbo dažnių sritį bei sumažinti lėtinimo koeficiento dispersiją.

Taigi aktualu ieškoti naujų automatizuoto lėtinimo sistemų tyrimo metodų, taikant dirbtinių neuronų tinklus, leisiančių surasti lėtinimo sistemų parametrus, išvengiant sudėtingų lėtinimo sistemų matematinių modelių sudarymo, pagreitinti skaičiavimus, išvengiant papildomos brangios įrangos naudojimo, ir išsaugoti sukauptas lėtinimo sistemų projektavimo žinias.

Disertacijoje sprendžiama spiralinių ir meandrinių lėtinimo sistemų su periodiniais netolygumais modeliavimo metodų tobulinimo ir jų tobulesnių konstrukcijų paieškos problema.

Tyrimų objektas

Darbo tyrimų objektas – nevienalytės periodinės lėtinimo sistemos ir jų modeliai bei analizės ir sintezės metodai.

Darbo tikslas

Darbo tikslas yra tobulinti sudėtingas turinčias periodinių netolygumų elektrodinamines spiralines ir meandrines lėtinimo sistemas bei ištirti jų analizės metodus, siekiant atskleisti nevienalyčių lėtinimo sistemų ypatumus ir jų automatizuoto projektavimo galimybes.

Darbo uždaviniai

Darbo tikslui pasiekti darbe reikia spręsti šiuos uždavinius:

1. Ištirti periodinių netolygumų įtaką nevienalyčių lėtinimo sistemų savybėms.
2. Ištirti spiralinių, meandrinių ir hibridinių lėtinimo sistemų, turinčių periodinių netolygumų, savybes.
3. Taikant dirbtinių neuronų tinklus sudaryti turinčių periodinių netolygumų lėtinimo sistemų automatizuotos analizės ir projektavimo algoritmus.
4. Imitacinių skaičiavimų būdu patikrinti siūlomų metodų veiksmingumą.

Tyrimų metodika

Darbe taikomi elektrodinaminio uždavinio sprendimo metodai, pritaikyti lėtinimo sistemų analizei – tai ilgųjų linijų, matricinis, daugialaidžių linijų ir skaitinis metodai, dirbtinių neuronų tinklų teorija. Lėtinimo sistemų kompiuteriniai modeliai ir sukurtieji algoritmai įgyvendinti, taikant programų

paketą Matlab[®] bei specialios paskirties programų paketus CST Microwave Studio[®] ir Sonnet[®].

Mokslinis naujumas

Rengiant disertaciją buvo gauti šie elektros ir elektronikos inžinerijos mokslui nauji rezultatai:

1. Sukurti nauji ilgosios linijos su periodiniais netolygumais modeliai bei metodai nevienalyčių plačiajuosčių periodinių sistemų užtvarinėms savybėms tirti bei gauti jų tyrimo rezultatai.
2. Taikant daugialaidžių linijų metodą sukurti algoritmai, leidę ištirti lėtinimo sistemos parametrų įtaką užtvarinės juostos pločiui, kurių rezultatai panaudoti spiralinių lėtinimo sistemų projektavimui.
3. Sukurti meandrinės, spiralinės bei hibridinės spiralė-meandras-spiralės sistemų matematiniai modeliai ir išvestos dispersinės lygtys, leidusios atskleisti lėtinimo sistemų periodinio nevienalytiškumo ir skersinio asimetriškumo įtaką sistemų dažninėms savybėms.
4. Taikant dirbtinių neuronų tinklus sukurta nevienalyčių elektrodinaminių lėtinimo sistemų dažninių charakteristikų skaičiavimo metodika, leidžianti nustatyti dažnines charakteristikas neišvedant sistemų dispersinių lygčių ir sudaryti dirbtinių neuronų tinklais paremti lėtinimo sistemų automatizuoto projektavimo algoritmai.

Praktinė vertė

Sudaryti elektrodinaminių lėtinimo sistemų tyrimo metodai ir iteraciniai skaičiavimo algoritmai, leidžiantys projektuoti lėtinimo sistemas, įvertinant sistemose esančius periodinius netolygumus, ir atskleisti naujausių konstrukcijų lėtinimo sistemų ypatumus. Sudaryti dirbtinių neuronų tinklais paremti lėtinimo sistemų dažninių charakteristikų skaičiavimo algoritmai, leidžiantys atsisakyti sudėtingų analitinių metodų ir paspartinti analizės ir sintezės procesus. Naudojant programinį paketą Matlab[®] sudaryta programinė įranga, leidžianti projektuoti lėtinimo sistemas.

Ginamieji teiginiai

1. Dėl periodinių netolygumų lėtinimo sistemos įgauna užtvarinių filtrų savybes, to priežastimi yra atsiradęs fazių skirtumo kampas tarp gretimų laidininkų įtampų ar srovių, siekiantis iki $\pi/2$ arba π radianų.
2. Turinčių periodinių netolygumų lėtinimo sistemų lėtinimo koeficiento dažninės charakteristikos dispersiją pavyksta sumažinti ir išvengti užtvarinės juostos, mažinant banginių varžų kitimo santykį išilgai laidininko iki 1,3 ir

didinant vienalyčių sričių ilgių santykį iki 1,5 bei mažinant nevienalytiškumo periodą, t. y. didinant nevienalyčių periodų skaičių išilgai laidininko vijos.

3. Padidinti meandrinį lėtinimo sistemų lėtinimo koeficientą ir įėjimo varžą ir garantuoti didesnę sistemos jautrumą galima papildant sistemą spiraliniu laidininku – naudojant hibridinę spiralė-meandras-spiralė sistemą.

4. Dirbtinių neuronų tinklais paremti algoritmai leidžia taikyti automatizuotus nevienalyčių lėtinimo sistemų projektavimo ir analizės metodus, neišvedant sistemų dispersinių lygčių.

Darbo apimtis

Darbo apimtis yra 116 puslapių, neskaitant priedų, tekste panaudotos 73 numeruotos formulės, 60 paveikslų ir 3 lentelės. Rašant darbą buvo panaudoti 128 literatūros šaltiniai.

Pirmajame skyriuje pateikiama literatūros analizė, aptariamos šiuo metu tyrinėjamos ir pramonėje taikomos lėtinimo sistemos. Apžvelgiami paplitę lėtinimo sistemų tyrimo metodai ir jų tendencijos. Aptariamos lėtinimo sistemų problemos ir būsimas autoriaus indėlis į nagrinėjamą problemą. Skyriaus pabaigoje formuluojamos išvados ir tikslinami disertacijos uždaviniai.

Antrajame skyriuje parinktos ilgosios linijos įėjimo varžos bei perdavimo koeficiento dažninių charakteristikų skaičiavimo metodikos, aptartos sudarytos programos ir pateikti tyrimo rezultatai, atskleidžiantys nevienalytiškumo įtaką lėtinimo sistemų savybėms.

Trečiajame skyriuje tiriamos turinčios periodinių netolygumų spiralinės, meandrinės ir hibridinės lėtinimo sistemos. Parenkamos sistemos įėjimo varžos, lėtinimo koeficiento ir užtvarinės juostos pločio skaičiavimo metodikos bei pateikiami jų tyrimo rezultatai.

Ketvirtajame skyriuje įrodomos galimybės automatizuotam lėtinimo sistemų projektavimui taikyti dirbtinių neuronų tinklus bei pateikiami lėtinimo sistemų tyrimo, taikant dirbtinių neuronų tinklus, rezultatai.

Bendrosios išvados

1. Parodyta, kad ištirti spiralinių ir meandrinų lėtinimo sistemų užtvarinės savybės įtakojančius rezonansinius reiškinius ir juos lemiančius veiksnius bei jų įtaką lėtinimo sistemų dažninėms savybėms galima sudarytais ilgosios ir daugialaidės linijos matematiniais modeliais, taikant analitinius matricių, ilgųjų ir daugialaidžių linijų metodus. Sudarytų modelių tyrimų rezultatų adekvatumas parodytas taikant specializuotų programų paketus CST Microwave Studio® ir Sonnet®, kuriuose skaičiavimai vykdomi baigtinių skirtumų laiko srities ir momentų metodais.

2. Tyrimais parodyta, kad dėl periodinių netolygumų ir nuo jų atsiradusių daugkartinių atspindžių, kai fazių skirtumo kampas tarp gretimų lėtinimo sistemos laidininkų įtampų arba srovių artėja prie $\pi/2$ arba π , lėtinimo sistemos įgauna užtvarinių filtrų savybių. Išvengti užtvarinių savybių pavyksta, mažinant banginių varžų kitimo išilgai laidininko santykį iki 1,3 ir didinant vienalyčių sričių ilgių santykį iki 1,5 bei mažinant nevienalytiškumo periodą, t. y. didinant nevienalyčių periodų skaičių išilgai laidininko vijos.

3. Tyrimais parodyta, kad didinant elektroninio įtaiso, turinčio kreipimo-lėtinimo sistemą, jautrumą ir naudojant meandro formos elektrodus su plačiu centriniu laidininku bei siaurais laidininkais kraštuose, svarbu išvengti meandrinio laidininko skersinio asimetriškumo, kuris perpus susiaurina elektrinio įtaiso pralaidumo juostą.

4. Naudojant hibridinę lėtinimo sistemą, t. y. kraštines meandrinio laidininko sritis keičiant spiralės formos vijomis, pavyksta 1,7 karto padidinti sistemos įėjimo varžą ir lėtinimo koeficientą.

5. Sudaryti dirbtinių neuronų tinklais paremti turintys periodinių netolygumų lėtinimo sistemų automatizuoto projektavimo algoritmai leidžia paspartinti tirtų spiralinės, meandrinės ir hibridinės lėtinimo sistemų sintezės ir analizės uždavinių sprendimą 465 kartus, išvengiant sistemų dispersinių lygčių išvedimo. Taikant dirbtinių neuronų tinklais paremtus metodus analizės uždavinio rezultatų skirtumas nuo etaloninių daugialaidžių linijų metodu gautų rezultatų neviršija 15 %, o parametrinės sintezės uždavinio rezultatų skirtumas nuo etaloninių neviršija 8 %.

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INVESTIGATION OF FREQUENCY PROPERTIES OF HELICAL AND
MEANDER SLOW-WAVE SYSTEMS

Summary of Doctoral Dissertation

Technological Sciences, Electrical and Electronic Engineering (01T)

Andrius KATKEVIČIUS

SPIRALINIŲ IR MEANDRINIŲ LĖTINIMO SISTEMŲ DAŽNINIŲ SAVYBIŲ
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