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Calculations of characteristics of microwave devices using artificial neural networks

***Abstract**. Using analytical iterative methods, simulation of microwave devices is complicated: computing time is relatively long, sophisticated models are used for simulations. Possibilities to improve simulation process were discovered using the method based on artificial neural networks. An example of the algorithm, which allows the transition from iterative calculations to neural networks and allows to avoid some modelling problems arising from the iterative calculations, is proposed in this paper.*

***Streszczenie.** Zastosowano nową metodę projektowania urządzeń mikrofalowych wykorzystująca sztuczne sieci neuronowe. W porównaniu z konwencjonalnie stosowaną metodą iteracyjną osiągnięto poprawę dokładności i szybkości obliczeń. (**Wyznaczanie charakterystyk urządzeń mikrofalowych z wykorzystaniem sieci neuronowych**)*

Keywords: neural networks, waveguides, helical structures, frequency characteristics.
Słowa kluczowe: urządzenia mikrofalowe, sztuczne sieci neuronowe.

Introduction

Retardation and waveguides systems are widely applied for travelling-wave tubes, delay lines, phase modulators or converters and other microwave devices [1–5]. Usually analytical iterative calculations are used to investigate the parameters of such systems. A simulation using analytical iterative calculations is a time consuming operation. This is usually 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 network techniques have been recognised as useful alternatives to conventional approaches in microwave modelling in recent years [6, 7]. In this paper the application of neural networks (NN) to simulate retardation or waveguides systems, not proposed in the literature yet, is analysed. An example of the algorithm, which allows the transition from iterative calculations to NN and allows avoiding some modelling problems arising from the iterative calculations, is proposed in this paper.

Algorithm based on neural networks

NN is the information processing system with its design inspired by the ability of the human brain to learn from observations and to generalise by abstraction. NN can be used in various microwave devices simulation tasks [8–12].

The simulation of microwave devices can be divided into 3 steps: initialization of system parameters; solving of transcendental linear dispersion equation system; evaluation the microwave devices electrodynamical parameters.

In this paper we propose an algorithm, where the NN helps to avoid difficult time consuming iterative calculations in finding the solutions of dispersion equations. NN place in the general microwave devices simulation procedure can be seen from the Algorithm 1. We use radial basis function (RBF) and multilayer perceptron (MLP) networks in our calculations.

The design and training procedure of the MLP, used for retardation and waveguide systems, is performed in four stages. Simple procedure is presented in Algorithm 2. In the first stage the training examples (frequency characteristics of retardation and waveguides systems) are collected by using the analytical iterative calculations.

It is necessary to increase the number of training data points to have a sufficient amount of training data for properly training of MLP. In the second training stage, in order to increase the number of training data points, the training examples, obtained by iterative calculations, are fed to the RBF for data interpolation.

Algorithm 1 The microwave devices simulation algorithm

A. Selection of the type of the material.
   1. Parameters of the material.
   2. Collection of calculated samples.
B. MLP training process.
   1. Interpolation.
   2. Grouping of features and targets.
   3. MLP training.
   4. Verification.
C. MLP simulation.
D. Adjustment of results after receipt of preferred characteristics.

Algorithm 2 The microwave devices simulation algorithm

A. Collecting samples for RBF network training.
   1. For retardation system: collection of retardation factor and input impedance dependences on the frequency.
   2. For waveguide system: collection of wave phase constant dependences on the frequency.
B. RBF network simulation.
C. MLP training.
   1. For retardation system: collection of retardation factor, input impedance and cut-off frequencies (in-dicating the calculation limits of the frequency) cha-racteristics dependences on the frequency, lengths and characteristic impedances of the homoge-neous segments.
   2. For waveguide system: collection of wave phase constant (indicating the calculation limits of fre-quency of the hybrid modes HE_{mn} and EH_{mn}) dependences on the frequency and waveguide permittivity.
D. Simulation of MLP.
   1. For retardation system: simulation of retardation factor, input impedance and cut-off frequencies characteristics dependences on the frequency.
   2. For waveguide system: simulation of wave phase constant dependences on the frequency.

The structure of the RBF is presented in the Fig. 1. The network has input, hidden and output layers. The hidden layer consists of neurons with Gaussian Radial Basis activation function. The parameters of the Gaussian functions are updated during the training of the RBF by minimizing the Euclidean distance between the actual and desired output of the RBF. During the RBF training, also the new neurons are added to the hidden layer of a RBF until it meets the specified mean squared error goal.

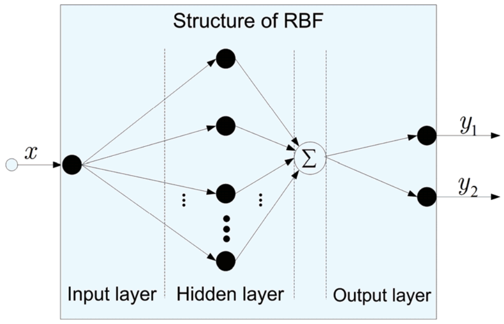


Fig.1. Structure diagram of the RBF, used for interpolation of the additional intermediate points

The third stage is performed by selecting the structure of the MLP. The structure of the MLP depends on the application and also on the received MLP training results. The training of the MLP is performed on the fourth stage of the design process and depending on the training results, the structure of the MLP can be updated (by changing the number of neurons in the hidden layer). The general structure diagram of the MLP is presented in Fig. 2. The MLP consists of one hidden layer with neurons combining its weighted inputs and biases and applying the specified transfer function. The output layer apply the weighted sum of the hidden layer outputs to the linear activation function.

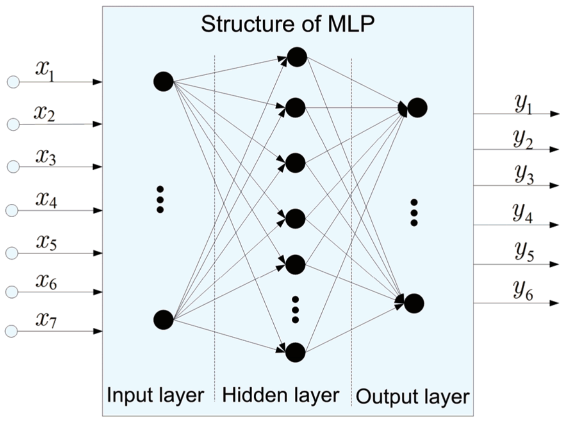


Fig.2. Structure diagram of the MLP, used for microwave device simulation

After discussion of the general algorithm based on NN, specific examples of the algorithm, used for solving of applications of retardation and waveguide systems, are presented in the next sections. The results, obtained by traditional methods and methods based on NN, are also compared.

Analysis of retardation systems containing periodical inhomogeneities

Various models of helical and meander structures containing periodical inhomogeneities and algorithms for computing of properties of such systems are proposed in [5, 13–18] and other papers. Reasons of periodical inhomogeneities are discussed in [5]. Analysis of such systems is relevance, because the systems obtain undesirable properties of stop-band filters due to periodical inhomogeneities.

For the investigation of such systems the iterative calculations and the multiconductor lines method are usually used. Using the fundamentals of the matrix algebra and iterations it is possible to find values of the wave number, corresponding to the given phase angle θ. After that it is possible to find values of retardation factor K_r, frequency f and input impedance Z_{IN} depending on the coordinate x:

(1) $$K_r = c_0/\upsilon_{ph} = \theta/kL ,$$

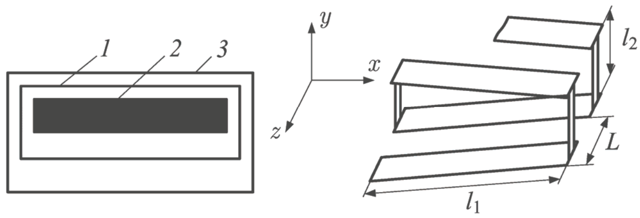
(2) $$f = kc_0/2\pi ,$$

(3) $$Z_{IN} = \frac{\underline{U}_{IN}(x)}{\underline{I}_{IN}(x)} ,$$

where: c_0 – the light velocity, υ_{ph} – the phase velocity of the travelling-wave, k – a wave number in vacuum, L – the step between neighbour conductors of the multiconductor line, $U_{IN}(x)$ and $I_{IN}(x)$ – voltages and currents of the conductors in the input of the multiconductor line depending on the coordinate x.

The use of iterative methods for the investigation of properties for helical and meander structures are faced with several problems. Primarily iterative computations takes a long time, because the method of approach is used for calculation. In addition, due to equations of voltages and currents are trigonometric functions, ambiguous solutions are obtained in calculations of the root of dispersion equation. Moreover it is possible to make a mistake detecting non-zero, but for example, the root of other spatial harmonics [12]. This happens when dispersion equation has two close solutions when θ approaches to π or $\pi/2$ depending on the type of retardation system which is used. The calculation accuracy and step selection are another problems which makes an influence on finding the correct solutions.

In order to avoid these problems it is proposed a new algorithm based on NN. Presented algorithm is suitable for both helical and meander retardation systems.



(a) (b)

Fig. 3. The cross-section of a helical system (a) and the view of the helix (b): *1* — helix; *2*, *3* — shields

The cross-section of a helical system and the view of the helix are presented in Fig. 3. Helical conductor consist of two homogenious sections with different lengths and characteristic impedances. The model of the helical system and the analysis using iterative multiconductor lines method is discussed in detail in [14]. Results of the helical system using iterative and NN methods are compared in Fig. 4.

Variation of characteristic impedance along the helix turn at values θ close to π (when the half of the wavelength in the system approaches the length of the helix turn) has caused radical changes of retardation factor and input impedance of helical systems and the stop band appears (Fig. 4). The central frequency f_c of the stop-band depends on the delay time t_d in the period of the system and is given by:

(4) $$f_c = 1/2t_d .$$

In order to reduce dispersion of retardation and width of the stop-band, we must reduce the ratio of characteristic impedances of homogeneous sections at $\theta = \pi$ and reduce the length of the section with less length.

In order to train MLP correctly, 45 data sets are obtained in the first stage of our algorithm using iterative method when varies frequency, characteristic impedances and lengths of homogeneous sections. The size of the matrix of every data set are 1x60 for input matrix and 2x60 for target matrix.

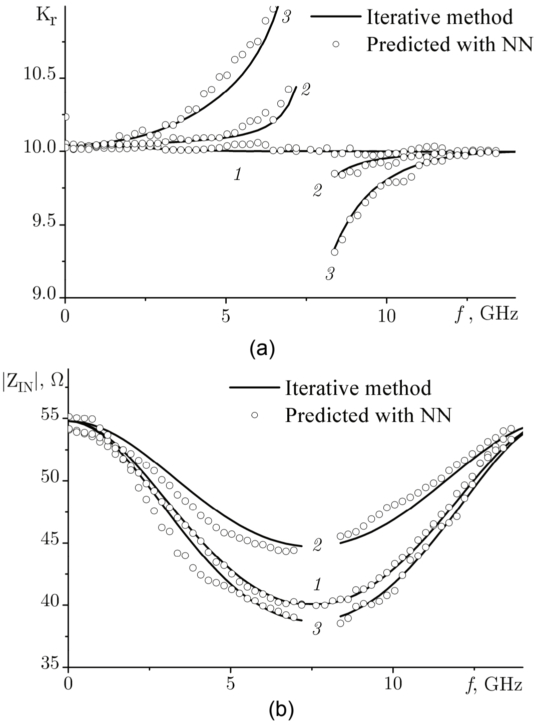


Fig. 4. Retardation factor (a) and input impedance (b) versus frequency at $l_1 + l_2 = 20$ mm, $L = 2$ mm, $l_1 = l_2 = 10$ mm and:

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

In order to increase the number of training data the RBF is used (Fig. 1). In the input layer of the RBF is one input and the input matrix consist of one frequency f parameter. In the output layer is one output and the target matrix consist of two K_r and Z_{IN} parameters. After RBF simulation input [f] matrix increased to 1x600 and target [K_r; Z_{IN}] matrix – 2x600.

The higher number of examples for the training of the MLP increases the accuracy of the network. The input layer of the MLP consist of seven neurons (frequency f; lengths of homogeneous segments l_1 and l_2; characteristic impedances of the homogeneous segments $Z_1(0)$, $Z_1(\pi)$, $Z_2(0)$ and $Z_2(\pi)$). The output layer consists of six neurons (retardation factor K_r; input impedance $Z_{IN}(x)$; four cut-off frequencies, indicating the calculation limits of frequency characteristics). The sizes of the general learning matrix is 7x27000 and the size of the general target matrix is 6x27000.

The proposed algorithm, based on NN, can also be used for the analysis of the meander systems. The model of the system and analysis using multiconductor lines method is discussed in detail in [16]. In this case MLP input layer consist of frequency f and six characteristic impedances of the homogeneous segments $Z_1(0)$, $Z_1(\pi)$, $Z_2(0)$, $Z_2(\pi)$, $Z_3(0)$ and $Z_3(\pi)$.

This meander structure is used in travelling wave deflection systems there it is necessary to have meander electrodes containing wide central parts of meander conductors and narrowed peripheral parts (Fig. 5). Then it is possible to increase the sensitivity of the travelling-wave tubes and impedance of its signal path. Results of the meander system investigation are presented in Fig. 6.

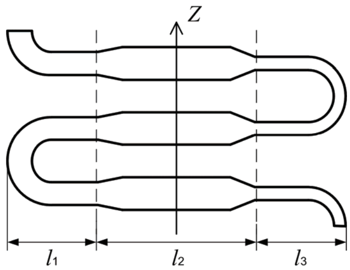


Fig. 5. The fragment of the asymmetrical meander electrode

According to analysis, retardation factor and input impedance of the system changes rapidly and the stop-band appears when phase angle θ along the meander conductor turn approaches to π. Increase of variation of characteristic impedances $Z(0)$ or $Z(\pi)$ is followed by increase of the width of the stop-band.

Results, obtained using NN, are similar to the results, obtained using iterative calculations. On the other hand, tolerances of the results obtained using NN vary from 5 to 15 percent, comparing with multiconductor line method. Tolerances vary as neural network has more difficulties in interpreting values of analysed edge areas of frequency characteristics.

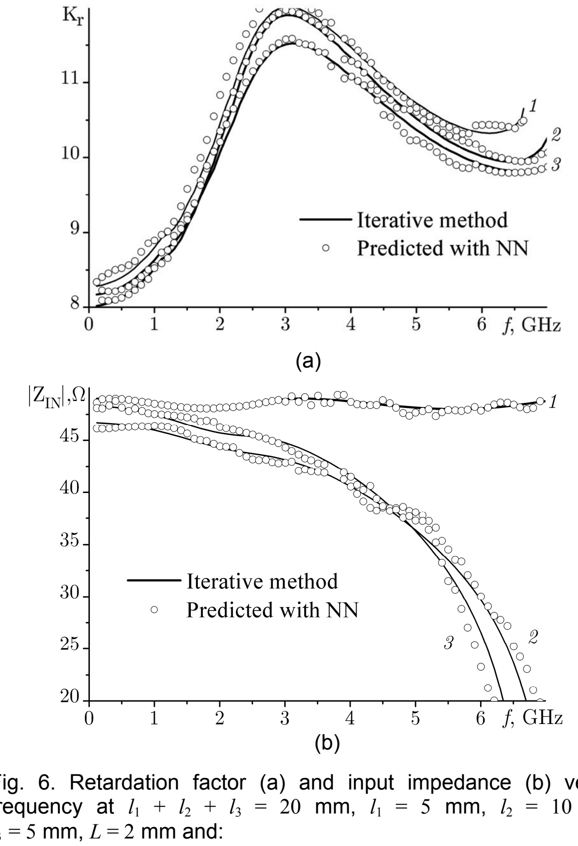


Fig. 6. Retardation factor (a) and input impedance (b) versus frequency at $l_1 + l_2 + l_3 = 20$ mm, $l_1 = 5$ mm, $l_2 = 10$ mm, $l_3 = 5$ mm, $L = 2$ mm and:

1 – $Z_1(0)$ = 60 Ω, $Z_1(\pi)$ = 40 Ω, $Z_2(0)$ = 60 Ω; $Z_2(\pi)$ = 40 Ω, $Z_3(0)$ = 60 Ω, $Z_3(\pi)$ = 40 Ω;
2 – $Z_1(0)$ = 60 Ω, $Z_1(\pi)$ = 40 Ω, $Z_2(0)$ = 50 Ω; $Z_2(\pi)$ = 30 Ω; $Z_3(0)$ = 60 Ω, $Z_3(\pi)$ = 40 Ω;
3 – $Z_1(0)$ = 70 Ω, $Z_1(\pi)$ = 50 Ω, $Z_2(0)$ = 50 Ω; $Z_2(\pi)$ = 30 Ω; $Z_3(0)$ = 70 Ω, $Z_3(\pi)$ = 50 Ω.

It is important to note that using both helical or meander models intermediate point's approximation using RBF took approximately 0.16 seconds with every data sample, when the number of examples is 7x60. The general data approximation time using RBF was 1.34 seconds. The learning process of the MLP took about 14 minutes. Finally, the calculations using the MLP took 0.01 seconds in the last stage of investigation, when the similar calculations using iterative method takes 4.65 seconds. Calculations were performed by medium-power PC using MATLAB© programming package.

Analysis of a cylindrical dielectric waveguides

The electrodynamical and mathematical models of cylindrical dielectric waveguides are presented in [3, 6]. Using these mathematical models, the dispersion equation is formed. For the calculation of dispersion equation usually are used iterative methods: Davidenko, Muller, secant, bisection and other [19, 20]. Calculations using these methods are time consuming. The cylindrical dielectric waveguide dispersion equations are presented in articles [21, 22].

Instead of the calculation of dispersion equation, the prediction of phase constant using MLP is used. The electromagnetic wave frequency and permittivity of dielectric waveguides are sent to the inputs of the MLP and in output of MLP is expected to get wave phase constant. The accuracy of the prediction depends on the MLP training success and the number of examples used. The examples, used during training of MLP, are received by using iterative methods.

To increase the number of examples, the interpolation of the training values using RBF is used. RBF is used to interpolate the phase constant (h') values for the frequencies (f), not calculated using the analytical method. The values of f are used as inputs and the values of h' are used as desired outputs for RBF during training phase.

The input layer of MLP has two inputs: the permittivity of dielectric waveguide ε_r and frequency of electromagnetic wave f. The output of MLP consist of one neuron and it is h'. The algorithm of Levenberg-Marquardt is used for MLP training.

Created algorithm can calculate main type HE_{11}, first higher EH_{11} and second higher HE_{12} modes of the waveguides. The wave propagation in dielectric waveguide dispersion characteristics can be calculated in range of permittivity $5 \le \varepsilon_r \le 20$.

The dispersion characteristics of wave propagation in dielectric waveguides are presented in Fig. 7, when permittivity is ε_r = 10. In figure there are compared the dispersion characteristics calculated using iterative methods and predicted with NN. Difference between calculation results is 4–5 % in range of frequency 60–100 GHz.

In Fig. 8 there are compared SiC dielectric waveguide dispersion characteristics calculated using iterative methods and predicted with NN, when temperature t = 1800 °C and permittivity ε_r = 11. The SiC electrodynamical parameters are taken from [22]. In frequency range 20–30 GHz difference between calculations is 7 %, in range of frequency 57–77 GHz difference between calculations and prediction is 5 % for main mode HE_{11}. For HE_{12} mode difference between calculations is 6 % in all range of mode.

In Fig. 9 there are presented dispersion characteristics of main mode HE_{11} and SiC dielectric waveguide dispersion characteristics for different temperatures. Using these characteristics differential phase shift modulus $|\Delta\vartheta|$ can be calculated, when $fr^d = \text{const}$.

Differential phase shift module was calculated by drawing the vertical line in waveguide working frequency range – Δfr^d. When the temperature of SiC waveguide is t_1 = 1800 °C the waveguide working normalized frequency range is Δfr^d = 0.0296 GHz·m. The vertical line is drawn at normalized frequency 0.04 GHz·m. The differential phase shift module can be obtained using equation:

$$|\Delta\vartheta|_{fr^d=\text{const}} = \Big|\Big(h_t' r^d - h_{1800^\circ}' r^d\Big)\Big|_{fr^d=\text{const}} \cdot L \cdot 360/2\pi,\ ^\circ, \qquad (5)$$

where h'_t – the wave phase constant in different temperatures; h'_{1800} – the wave phase constant at 1800 °C ; L – the waveguide length.

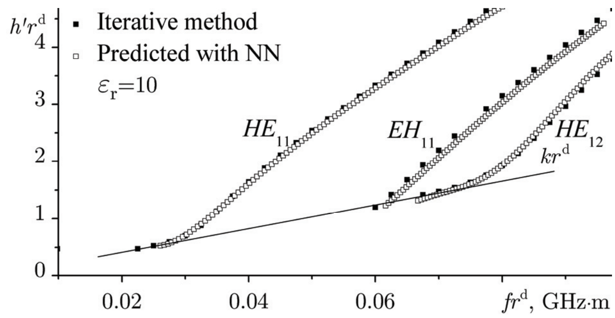


Fig. 7. Dispersion characteristics of wave propagation in dielectric Waveguides

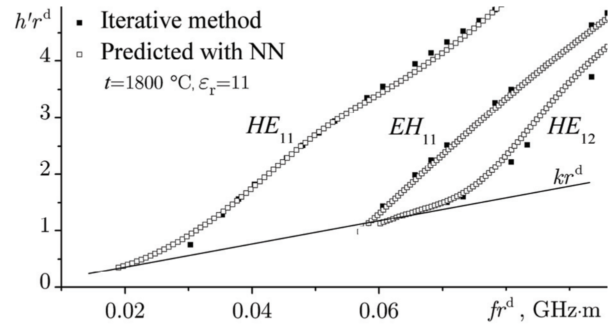


Fig. 8. Dispersion characteristics of wave propagation in dielectric waveguides, when t =1800 °C; ε_r= 11

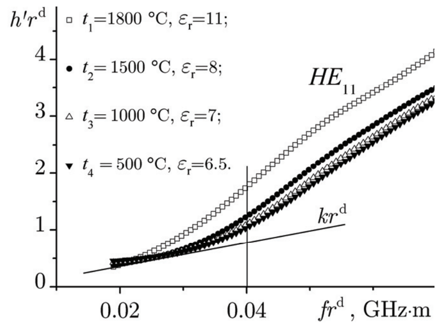


Fig. 9. Mode HE_{11} dependencies on the different temperature

Decreasing the temperature t, the dispersion characteristics of the SiC waveguides moves to higher frequency side. In this situation the differential phase shift module is changing. These calculation results usually are used for the design of various microwave devices.

For the design of the microwave devices the $|\Delta\vartheta|$ is a very important parameter. When the slope of $|\Delta\vartheta|$ goes more perpendicular, it means that the phase shift in frequency range also increases, the phase shifter working range is wider in $|\Delta\vartheta|$ and narrower in the temperature range. These features are very useful for phase shifters.

The differential phase shift module dependences on the temperature are presented in Fig. 10, when SiC waveguide length $L = 8$ mm. Here are compared the results of differential phase shift module calculations using iterative methods and NN.

Difference between calculations results is the biggest, when temperature is 525 °C. Increasing the temperature of SiC waveguide the difference between calculation results is decreasing and in temperature 823 °C difference between results is ~0.1 %. Then increasing the temperature, the difference between results of calculation is grooving and became equal to 9 % at temperature 1350 °C.

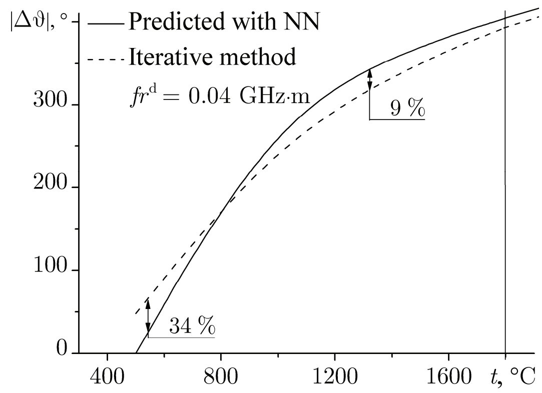


Fig. 10. The differential phase shift module dependences on the temperature

The similar investigation results are presented in the book [22], there to calculate dispersion characteristics of the waveguides is used partial area method.

The SiC phase shifter working range of the temperature is $(500 \le t \le 1800)$ °C and difference phase shift module is changing in the range $0^\circ \le |\Delta\vartheta| \le 400^\circ$. The SiC waveguides are very small, with diameter of one millimetre and they can work in high temperatures. Accordingly they can be used in phase shifters and phase modulators. With these functional features they can be integrated into radio frequency (RF) systems, receivers or transmitters and other microwave systems. There they can be used as phase shifters, which working range is controlled using differential phase shift modulus dependences on the temperature. Also the created algorithm for cylindrical dielectric waveguide calculation using NN can be adapted for waveguide, cut-off frequencies, and broad bandwidth calculation.

Using iterative methods calculation time is about 63 seconds for 56 iterations of frequency f. The calculation time for these characteristics using NN are 0.02 seconds. And it is 2100 times faster than using iterative methods.

Conclusion

Due to periodical inhomogeneities and multiple reflections from them helical and meander retardation systems obtain undesirable properties of the stop-band filters. Neural network (NN) can be used in investigation of retardation systems. NN allows to improve time consumption of the modeling process and to solve some specific problems arising using iterative methods.

The created algorithm allows quickly calculate SiC waveguides main three dispersion characteristics. The SiC waveguides can be used in microwave shifters, in temperature range $(500 \le t \le 1800)$ °C.

To ensure accurate learning process and to decrease the number of learning attempts, it is very important to select the correct training data.

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