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Electromagnetic Modeling of Microstrip Elements Aided with Artificial Neural Network

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***Abstract*—The electromagnetic modeling principle aided with artificial neural network to designing the microwave wideband elements/networks prepared in microstrip technology is proposed in the paper. It is assumed that the complete information is known for the prototype design which is prepared on certain substrate with certain thickness and electric permittivity. The longitudinal and transversal dimensions of new design are calculated separately using the scale coefficients which are determined from transmission line equation. Next the artificial neural network can be used for final tuning which should take into account the dispersion of microstrip line. The verification of proposed procedure is shown for exemplary planar UWB balun.**

***Index Terms*—planar balun, artificial neural networks, electromagnetic modeling**

I. INTRODUCTION

Precise design of microwave planar element/network was always the challenge for RF engineers. Decades ago before the powerful computer and fullwave simulators were widely used the designing procedure consisted of few steps. The first one was creating the analytical model (usually physical one) as exact as possible. Such models were often based on lumped elements and/or transmission line approaches. It was justified since the most of microwave planar networks consisted of these two kinds of elements. The next steps was to find the solutions which was usually inaccurate. The final corrections was made after the experimental verifications of the design and took into account the deviation between theoretical model and measurement results. Sometimes the corrections terms were applied if physical effect could be written via analytical formula. As an example we can consider the theory of filters design when the design procedure begin with the filter prototype. Next the equivalent planar model can be created using e.g. Kuroda transforms [1]. Finally the end effect had to be taken into account using some correction terms [2] or results of experimental verifications (especially for higher frequencies). The situation was completely changed when fullwave simulators appeared and could solve the Maxwell's equations directly. In fact we need only *planar model* of network/element for designing. Note that the planar model has now the function of the *protype* and fullwave simulator prepares the current design according to our current needs (new substrate, new operation frequency). However, the time of calculation of fullwave simulators is still a limiting factor for more complicated structures so the proper choice of starting point to simulation is of great importance.

A new procedure of microstrip elements designing is proposed for the elements for which the information on the parameters of the prototype is known. We propose that the procedure consists of two steps:

- the approximate design using the principles of em modeling based on transmission line model,
- the final tuning of approximate design by using artificial neural network (ANN).

This ANN learning for prototype using fullwave simulator is done only one time and next ANN can be used for any new design.

In the Section II of the paper the principle of em modeling is presented. It is shown that the scaling of the longitudinal and transversal dimensions of new (current) design are found from different formulas. For longitudinal dimensions which could be comparable to wavelenght the similarity constants are introduced to transmission line equations. Transversal dimensions are established from the condition based on the characteristic impedance identity of prototype and current design. The information on ANN applied for final tuning of the design is shown in Section III. Section IV describes application of presented theory to the case of UWB balun structures. Section V summarizes the results of study

II. THEORY OF EM MODELING FOR MICROSTRIP-BASED MICROWAVE ELEMENTS

The section of microstrip line is two-dimensional element with lenght generally comparable to wavelenght whereas the width is much smaller than wavelenght. For this reason the modeling can be done separately for both dimensions.

A. Longitudinal dimensions modeling

Microstrip line is quasi-TEM waveguiding structures so we can use the transmission line equation for em modeling in the first approximation. The dispersion effect is omitted since we expect that introduced error will be taken into account when ANN is applied. In fact in learning process we use the data from fullwave simulator where dispersion effect is present.

We write the transmission line equation for microstrip line:

$$\frac{\partial I^{(q)}}{\partial z^{(q)}} = -\mathcal{C}^{(q)} \frac{\partial V^{(q)}}{\partial t^{(q)}} \tag{1}$$

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where index q concerns prototype (p) and nd new (current) design. Now we define the similarity constants for variables from eq. (1):

$$\alpha_\Gamma = \Gamma^{(p)}/\Gamma^{(nd)} \tag{2}$$

where Γ is the parameter under consideration. We introduce (2) to (1) for the case of the new (current) design. This yields:

$$\frac{\partial I^{(p)}}{\partial z^{(p)}} = -C^{(p)} \cdot K \cdot \frac{\partial V^{(p)}}{\partial t^{(p)}} \tag{3}$$

where coefficient K is equal:

$$K = \frac{\alpha_t}{\alpha_l} \cdot \frac{\sqrt{\varepsilon_{eff}^{(nd)}}}{\sqrt{\varepsilon_{eff}^{(p)}}} \tag{4}$$

In (4) the similarity constants α_t and α_l correspond to the time and the length (in z direction) variables, respectively. For microstrip line characterization we apply the commonly used efficient permittivity of substrate - in this approach it was calculated as [3] :

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \cdot \frac{1}{\sqrt{1 + 12h/w}} \tag{5}$$

Note that the choice of $K = 1$ but different similarity constants in (4) means that the problems of prototype and new (current) design are similar. We can expect theoretically the same parameters of the prototype and new (current) design. The similarity constant $\alpha_t = \alpha_f^{-1}$ so taking $K = 1$ longitudinal dimensions $z^{(nd)}$ of new (current) design can be found from the dimesions $z^{(p)}$ of the prototype [4]:

$$\frac{z^{(nd)}}{z^{(p)}} = \frac{f_0^{(p)}}{f_0^{(nd)}} \cdot \frac{\sqrt{\varepsilon_{eff}^{(p)}}}{\sqrt{\varepsilon_{eff}^{(nd)}}} \tag{6}$$

where f_0 is the frequency of modeling.

B. Transversal dimensions modeling

Transversal dimensions of the section of microstrip line are much smaller than wavelenght so the propagation model is not necessary in this case. In most of the cases the sections of microstrip line forming the microwave elements are specified by their characteristic impedances. We will assume in the first approximation that the characteristic impedances of the prototype and new (current) design should be equal:

$$Z_c^{(p)} = Z_c^{(nd)} \tag{7}$$

We used in our study analytical formula (2.18) from [3] which can be written in simplified form as:

$$w = F(h, \varepsilon_r, Z_c) \tag{8}$$

where w is the width of microstrip whereas h and ε_r are the substrate thickness and its relative permittivity, respectively.
It is worth noticing that ANN used in final tuning should take into account the errors resulting from this approximation since it was learned using fullwave simulations. Using (7) and (8) we can calculate the width of new design as:

$$w^{(nd)} = F^{(p)}(h^{(nd)}, \varepsilon_r^{(nd)}, Z_c^{(p)}) \tag{9}$$

Hereby we can calculate longitudinal and transversal dimensions of microstrip sections forming microwave element which is the scaled version of the prototype. After these calculations we can use (if necessary) ANN which should correct the mistakes introduced by simplifying assumptions. The input reflection coefficient is key parameter of most of microwave elements so final tuning will concern its minimization in the frequency band.

III. ANN as the Final Tuning Design Tool

A special ANN was applied to correct the mistakes which were introduced by important simplifying assumptions. Basic information on ANN used are as follows:

- FF-MLP (Feed Forwarded MultiLayer Perceptron) has been used with one hidden layer, error back-propagation learning (Levenberg-Marquadt, matlab function *trainlm*),
- sigmoidal transfer function in hidden layer and linear one in output layer were applied,
- learning vector consisted of 102 elements (51 real parts od S_{11} and 51 imaginary parts of S_{11} calculated for 51 frequencies of frequency bandwidth),
- pseudo random sampling LHS (*Latin Hypercube Sampling* [5]) has been used to collect the learning vectors.

Learning vectors were generated from Keysight ADS MOMENTUM. On the begining of designing it is important to determine which level of the errors of dimensions (learning errors) is acceptable from the point of view of reflection coefficient characteristics. After careful study we found that the level of normalized learning error 10^{-5} corresponds to acceptable error in reflection characteristics. During the study it was also specified that the optimal number of neurons in hidden layer is 45 and 100 learning vectors should be used in learning process to avoid the over-learning.

IV. Verification of the Theory

The UWB balun consisting of the sections of microstrip lines has been chosen as a prototype to verify the theory. We used the structure proposed in [6]. As a substrate RF-35 has been used with electric permittivity $\varepsilon_r = 3,5$ and thickness 0,762 mm. The structure of balun is shown in fig. 1 and the input reflection coeeficient is shown in fig. 2. At the begining the dimesions which have little influence on the parametrs of balun have been determined. It is important step because it permits to limit the numerical efforts necessary to create ANN - the dimension of output layer depends on number of dimensions to be optimized. The study showed that only 9 of 15 dimensions which define the geometrical structure of balun influence on its input matching. They were the lenghts ($L1$ - $L4$) and the widths ($W1$ - $W4$) of microstrip sections and parameter P. After this preliminary step the ANN was created and learned according to the data presented in the previous section.

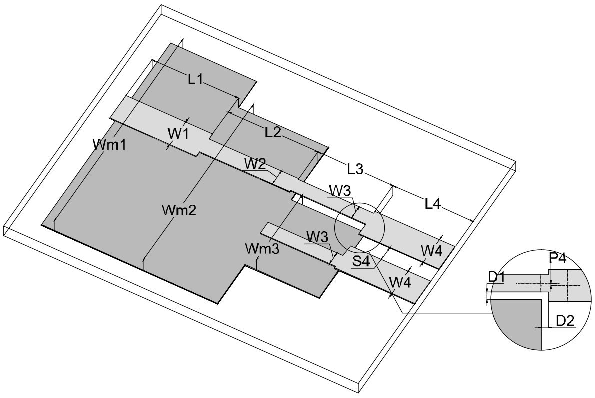

Fig. 1. Microstrip planar UWB balun

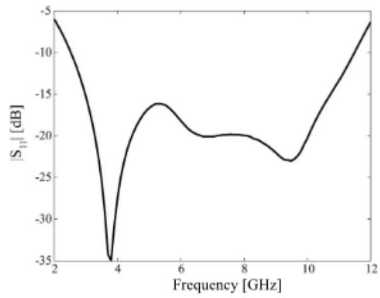

Fig. 2. Input reflection coefficient of the prototype UWB balun presented in fig. 1

A. Case A - change of the substrate

We used the prototype to design balun on the substrate Rogers RT Duroid 6006 with electric permittivity $\varepsilon_r = 6,45$ and thickness 0,635 mm so the similarity constants are 1,84 and 0,83, respectively. The input reflection coefficient of new design after em modeling is shown in fig. 3. We can

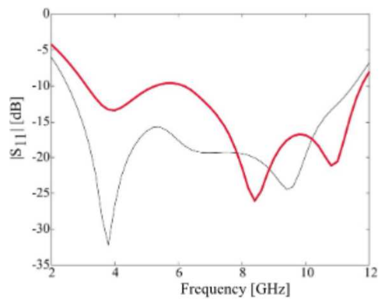

Fig. 3. Reflection coefficient of new design of UWB balun (the case of substrate modification) after em modeling (red curve) as compared to the curve for the prototype (black curve)

observe the deterioration of the matching especially for lower frequencies, however reflection coefficient is still below - 10 dB. After using ANN (fig. 4) the matching is better for lower frequencies and the curve is more flat for higher frequencies. We use the generalization coefficient to characterize the improvement introduced by modeling and ANN. After modeling the coefficient was 0,126 whereas after application of ANN 0,112. Note that the the improvement of the generalization coefficient is about 0,01 but visually the improvement of the chacateristic seems be clearly noticeable.

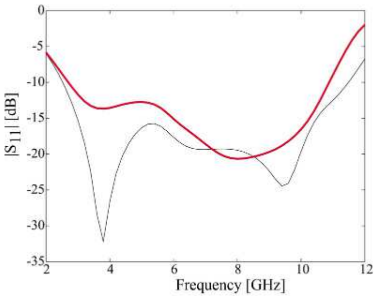

Fig. 4. Reflection coefficient of new design of UWB balun (the case of substrate modification) after em modeling and ANN application (red curve) as compared to the curve for the prototype (black curve)

B. Case B - change the frequency of operation

We also design UWB balun for operation in different frequency range. The central frequency of operation of prototype was chosen as 6,85 GHz (lower and upper frequencies of prototype were 3,5 GHz and 12,5 GHz, respectively). We use the em modeling to design balun using the same substrate but for central frequency equal 3,5 GHz. The input reflection coefficient of new design after em modeling is shown in fig. 5. It is observed good result of the modeling - the matching is good in all frequency band and additionally the curves for prototype and new design are similar. Application of ANN (see

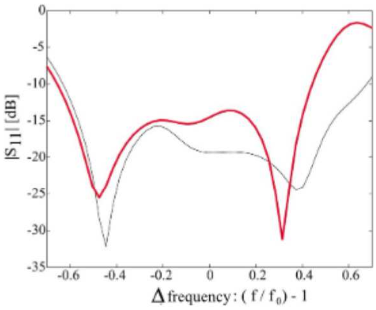

Fig. 5. Reflection coefficient of new design of UWB balun (the case of operation frequency change) after em modeling (red curve) as compared to the curve for the prototype (black curve)

fig. 6) leads to further improvement of balun parameters. It is observed for higher frequencies and it gives the improvemetnt of the generalization coefficient from 0,18 to 0,14.

V. CONCLUSION

The procedure of the designing the microwave planar elements consisting of the sections of microstrip line is presented. It is assumed that the complete information for the prototype design is known. In the first step the procedure applies the principle of em modeling of TEM lines to calculate the preliminary dimesions of new design. Next the ANN is used to minimize the mistakes resulting from quasi-TEM approximation of em

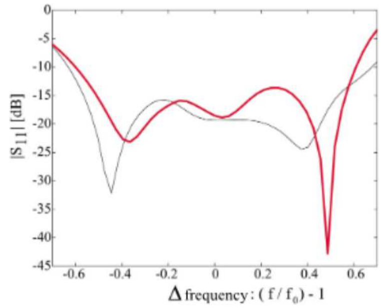

Fig. 6. Reflection coefficient of new design of UWB balun (the case of operation frequency change) after em modeling and ANN application (red curve) as compared to the curve for the prototype (black curve)

wave propagation in microstrip line. The proposed procedure was verified for the case of UWB balun. The results of designing are shown for the case of changing the substrate and the frequency of the operation of the balun.

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