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Design of Microstrip UWB Balun Using Quasi-TEM Approach Aided by the Artificial Neural Network

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Abstract—The design procedure for UWB balun realized in the microstrip technology is proposed in the paper. The procedure applies Artificial Neural Network which corrects the dimensions of the approximate design found by appropriate scaling of the dimensions of the prototype. The scale coefficients for longitudinal and transverse dimensions of microstrip lines are determined from electromagnetic modeling based on transmission line equations. The scaling procedure of radial stubs is also proposed. The design procedure was verified experimentally for exemplary balun with radial stub.

1. INTRODUCTION

Microstrip ultra-wideband (UWB) baluns are widely used in antenna technique to feed the planar antennas with symmetrical input through a microstrip line. The precise design of a planar UWB antenna with baluns seems simple because full-wave simulators are more and more available. However, the antenna layout may be large and complex in this case, so the time of simulations can be a factor limiting the design efficiency. Thus numerically efficient methods for the design of a UWB antenna with integrated balun are proposed to limit time-consuming full-wave calculations [1, 2].

The approach presented in [1] is numerically efficient for the initial research of new structures when the extensive numerical calculations are necessary. However, it does not appear optimal for the case of known layout because it does not apply the experience gained while designing the layout for the first time.

We propose in the paper a design procedure for UWB microstrip baluns based on the concept of the prototype. As a prototype we understand the balun layout with complete information on the dimensions and substrate parameters. The electrical parameters of the prototype which fulfill the specified requirements in the frequency range are calculated using full-wave simulator. The proposed procedure applies Artificial Neural Network (ANN) which is learned through full-wave simulations of the prototype. Let us assume that we want to design the balun with the same layout like in the prototype but on a different substrate. We will call this project as the current project. The approximate design of the current project is based on the electromagnetic modeling of the microstrip line using transmission line equations. Such modeling is an effective tool for the approximate broadband modeling (small dispersion effects of microstrip line) and leads to the simple analytical formulas for the scaling coefficients. ANN is then used to correct the dimensions of the approximate design of the current project.

ANN learned by full-wave simulations offers good precision with reduced numerical costs compared to repeated full-wave simulations, so it is used in rf/microwave components design (e.g., [3, 4]).

The paper is organized as follows. The description of the proposed procedure with remarks on its numerical efficiency is shown in Section 2. The principle of em modeling of microstrip line section based on the transmission line equation is presented in Section 3 whereas Section 4 presents simplified

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modeling of the stubs. More details on the application of ANN in the proposed procedure are described in Section 5. Results of experimental verification of the design procedure for exemplary UWB balun are presented in Section 6. Section 7 summarizes the results of the study.

2. DESIGN PROCEDURE

The flowchart of the proposed design procedure is shown in Fig. 1.

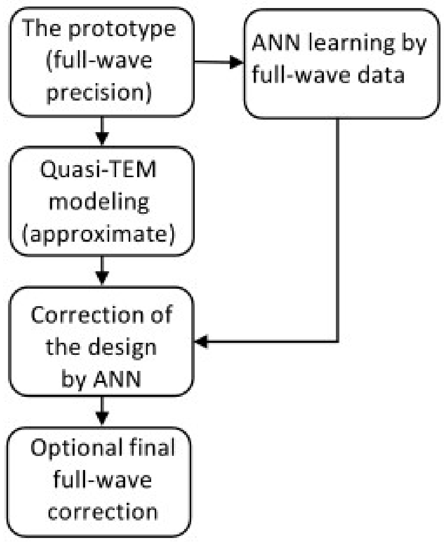


Figure 1. The flowchart of the design procedure.

The design procedure consists of the following steps:

(i) the approximate design applying Quasi-TEM modeling of the microstrip line. The dimensions of the current project layout are calculated using the scaling coefficients. These coefficients for transversal and longitudinal dimensions of the microstrip line sections are found from the modeling based on the results of the dimension analysis [5, 6] applied to the transmission line equations,

(ii) correction of the dimensions of the current project by using ANN. This step gives the accuracy of the project comparable to full-wave simulations, but it does not require significant numerical efforts. Once learned ANN quickly performs the calculations for various new projects,

(iii) optional final full-wave correction.

The examination of the time of calculations for the proposed design procedure leads to the following conclusions:

(i) full-wave simulations are performed to create the prototype. However, these calculations are made only once for a given layout. They appear for any design procedure, so they are neutral when we compare the proposed procedure with other ones from the point of view of numerical efficiency,

(ii) full-wave simulations are also performed to learn ANN using the prototype. This time element strongly depends on the complexity of layout and the numbers of frequency points used to learn ANN. We used 51 frequency points to cover the range 2–12 GHz for microstrip balun designed for UWB standard. In the case of microstrip balun with the radial stub (used to verify the design procedure — see Section 6) 350 training samples were applied to 6 parameters to be optimized. However, this procedure applied to UWB balun with the rectangular stub [7] needs only 100 training samples for 9 parameters to be optimized.

3. TRANSMISSION LINE EQUATIONS MODELING OF THE MICROSTRIP LINE SECTION

The lengths and widths of the microstrip line sections of the baluns differ significantly in the dimensions with respect to the wavelength, so they are modeled separately.

3.1. Modeling of the Transversal Dimensions

When we use the concept of the prototype, the characteristic impedance of the line sections for the current project (superscript cp) remains unchanged as compared to the prototype (superscript p):

$$Z_c^{(cp)} = Z_c^{(p)} \tag{1}$$

We can find in the literature the analytical formulas $F_Z(*)$ (e.g., [8, 9]) relating the dimensions of the microstrip line and the electric permittivity of the substrate with its characteristic impedance. As a result we can calculate the width of the microstrip line for the current project $w^{(cp)}$ as:

$$w^{(cp)} = F_Z\left(h^{(cp)}, \varepsilon_r^{(cp)}, Z_c^{(p)}\right) \tag{2}$$

where h and ε_r describe the thickness and electric permittivity of the microstrip line, respectively. The knowledge of the parameters of the microstrip line permits the calculation of the effective permittivity for the current project $\varepsilon_{eff}^{(cp)}$ which will be useful in modeling the longitudinal dimension of the microstrip line section.

3.2. Modeling of the Longitudinal Dimensions

We apply the equations for modeling the microstrip line. According to the dimension analysis we define similarity coefficients for the longitudinal dimension and frequency:

$$\alpha_l = l^{(p)}/l^{(cp)} \quad \alpha_f = f^{(cp)}/f^{(p)} \tag{3}$$

Next we introduce them to the transmission line equations and apply the condition of similarity of the problems [7]. As a result we find the longitudinal dimension of microstrip line section for current project $l^{(cp)}$ as a function of the length and operation frequency of the prototype [10]:

$$l^{(cp)} = l^{(p)} \cdot \frac{f_0^{(p)}}{f_0^{(cp)}} \cdot \frac{\sqrt{\varepsilon_{eff}^{(p)}}}{\sqrt{\varepsilon_{eff}^{(cp)}}} \tag{4}$$

where ε_{eff} is the effective permittivity of the microstrip line, and f_0 is the frequency of modeling. Note that the dispersion in microstrip line is not very important, so we can choose the central frequency of UWB as the frequency of modeling for whole frequency range.

4. THE RECTANGULAR/RADIAL STUBS MODELING

The rectangular stubs are in fact the short sections of the microstrip lines, so we can directly use (2) and (4) for scaling the transversal and the longitudinal dimensions of the microstrip line section, respectively.

For approximate modeling of the radial microstrip stub (Fig. 2), we applied a simple model which treated the stub as a cascade of very short sections of the microstrip lines with variable widths [11].

The geometry of the stub is described by two variables: the radius r and opening angle α_s. The radius is treated in our approach as the sum of short sections of microstrip lines, so it can also be modeled using formula (4). Note that the application of formula (4) needs a definition of the equivalent effective permittivities which are different for each of the section. We have chosen the arithmetic average of the

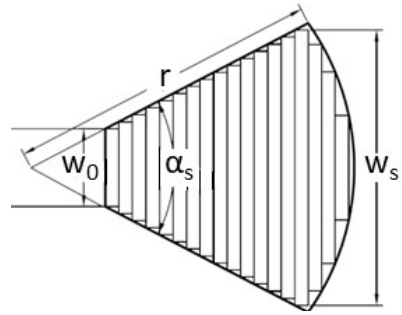


Figure 2. Layout of microstrip stub.

effective permittivities of the narrowest and widest sections of the microstrip line [10]. The opening angle can be found from geometrical relations (see Fig. 2):

$$\alpha^{(cp)} = 2 \arcsin\left(\frac{w_s^{(cp)}}{2 \cdot r}\right) \tag{5}$$

where $w_s^{(cp)}$ is calculated according to the modeling of short section of lines (see (2)). The exemplary results of the modeling of the radial stub are presented in Fig. 3. The frequency of modeling was $f_0 = 7\,\text{GHz}$. The prototype was designed on Taconic RF-35, $\varepsilon_r = 3.5$, $h = 0.762\,\text{mm}$, whereas the current project concerned Rogers Duroid RT 6006, $\varepsilon_r = 6.45$, $h = 0.635\,\text{mm}$.

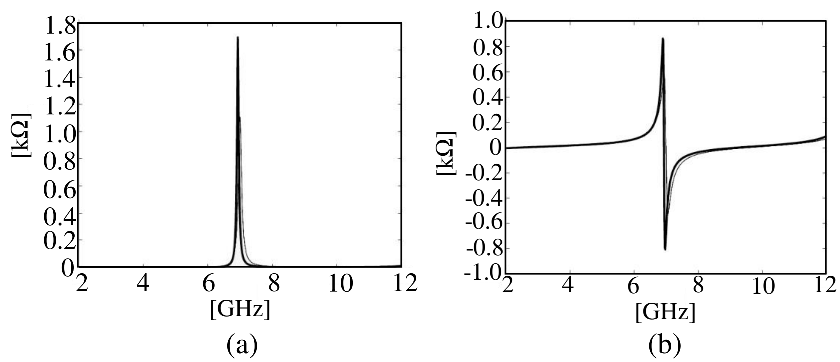


Figure 3. The resistances and the reactances of the prototype (thick lines) and the current project (thin lines) for the exemplary microstrip stub, (a) resistance, (b) reactance.

We expected that the errors introduced by such coarse approximations would be corrected by ANN which was learned by the results of the full-wave simulations (Keysight ADS MOMENTUM).

5. APPLICATION OF ANN IN THE DESIGN PROCEDURE

Microstrip UWB balun [12] operating in the frequency range 3.1–10.6 GHz has been chosen to verify the design procedure (Fig. 4). The prototype was designed on an RF-35 substrate (thickness $d = 0.762\,\text{mm}$, $\varepsilon_r = 3.5$) for central frequency $f_0 = 6.85\,\text{GHz}$. S_{11} is a fundamental parameter of the balun, so it was chosen to train ANN to correct balun dimensions according to the requirements formulated for current design. It was found that the learning vector consisting of 102 elements (51 real parts and 51 imaginary parts of S_{11} calculated for 51 frequencies covering the frequency range 2–12 GHz) leads to the acceptable normalized learning error (10^{-5}). We observed that further reducing the error does not lead to apparent differences in the characteristics of the reflection coefficient.

We used standard Feed Forwarded MultiLayer Perceptron (FF-MLP) with one hidden layer, the error back-propagation learning, sigmoidal transfer function in the hidden layer, and the linear one

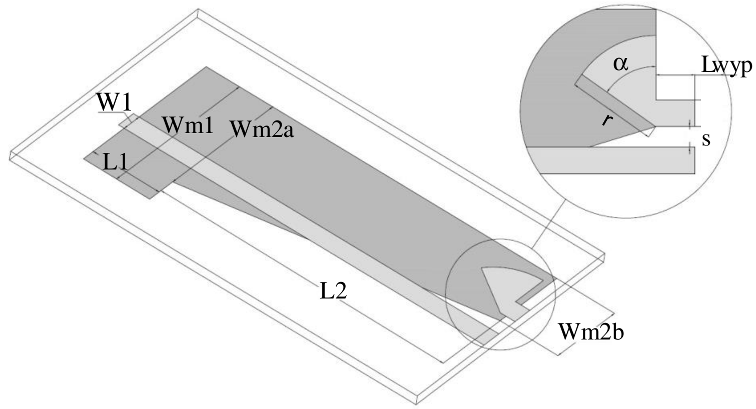


Figure 4. UWB microstrip balun structure.

in the output layer. Pseudo random sampling LHS (Latin Hypercube Sampling [13]) has been used to optimize the collection of learning vectors which needs the time-consuming full-wave simulations. Generally available MATLAB procedure *trainlm* has been used.

It is seen in Fig. 4 that 10 parameters describe the balun layout. We expected that not all the dimensions have to significantly affect S_{11} of the balun. The significance factor (SiF) based on the generalization error has been introduced [10] to verify which dimensions can be excluded from the learning process without significantly decrease in the accuracy of the design. Full-wave simulations showed that we can eliminate the variables W_{m1}, s, L_{wyp} and α if SiF value was 0.02.

Full-wave simulations were next performed for each of 6 dimensions in the terms of their deviations $\pm 20\%$ from the optimal values to learn ANN about how the changes of the balun dimensions affect S_{11} characteristics. The assumed learning error was achieved for 36 neurons in the hidden layer and 350 training samples.

We have chosen the substrate Rogers RT Duroid 6006 (thickness $d = 0.635\,\text{mm}$, $\varepsilon_r = 6.45$) for the current project, and the central frequency was unchanged ($f_0 = 6.85\,\text{GHz}$). The scaling of the prototype (see Sections 3 and 4) was done (Fig. 5(a)), and next we corrected the dimensions of layout using ANN (Fig. 5(b)). It is seen that even this approximate design gives $|S_{11}|$ less than $-10\,\text{dB}$ in whole UWB band, the application of ANN improves $|S_{11}|$ on average by 3 to 5 dB. Recall that the objective of proposed procedure is to reproduce the scattering parameters for current project as close as possible to the parameters of the prototype. We observe from Fig. 5(b) that $|S_{11}|$ characteristic for current design is shifted with maximum values about $-14\,\text{dB}$. We tried to lower these maxima by

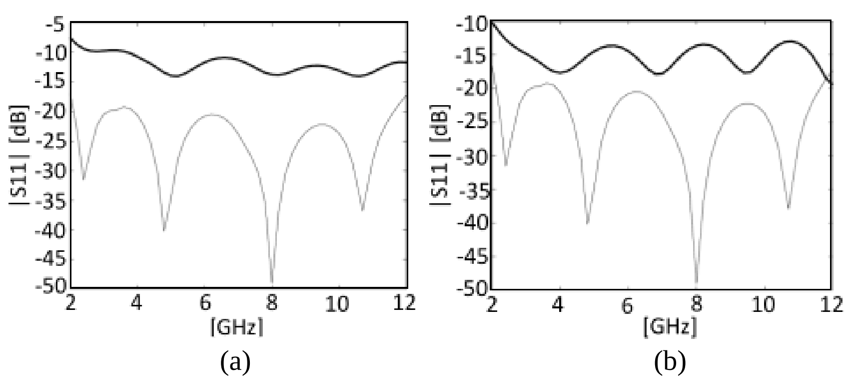


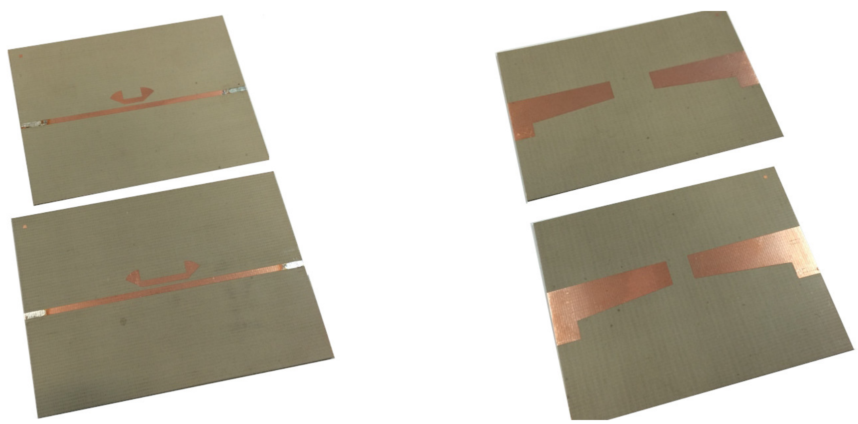
Figure 5. Reflection coefficients of the balun designed on RT Duroid 6006 (thick line) compared to the prototype designed on RF-45 (thin line) (a) after application of the scaling procedure; (b) after application the scaling and ANN.

full-wave simulations (the last step of procedure in Fig. 1), but the improvement of $|S_{11}|$ characteristics was practically imperceptible in the entire UWB. Thus we can suppose that the procedure leads to optimal parameters for the given substrate.

The deterioration of the reflection properties in the current projects as compared to the prototype can be explained by the hybrid nature of excited quasi-TEM mode. Note that the prototype was designed for the substrate with relative low electric permittivity ($\varepsilon_r = 3.5$) whereas the current project uses the substrate with about twice higher electric permittivity. In the latter case, the hybrid nature of quasi-TEM mode is more noticeable, which can lead to the deterioration of the reflection properties of the balun.

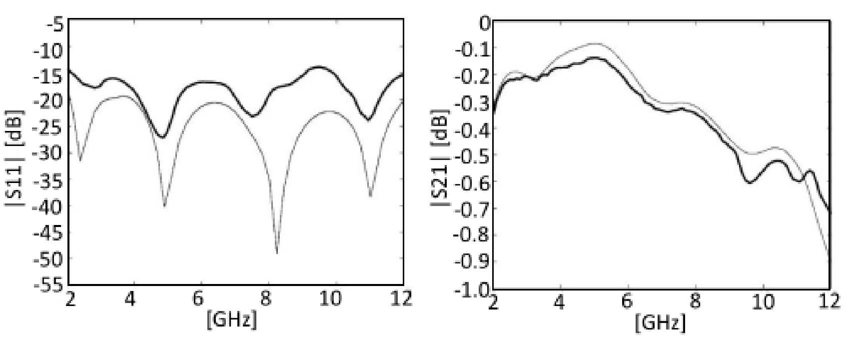
6. EXPERIMENTAL VERIFICATION OF THE DESIGN PROCEDURE

The balun output consists of coplanar microstrips, so we have no direct access to VNA input. The back-to-back (b2b) configuration is commonly used in such a situation, and the scattering parameters of the tested network are then extracted using the suitable method. We used the method proposed in [14]. Photos of the fabricated prototype of the balun are shown in Fig. 6. In Fig. 7 the scattering parameters extracted from the results of measurements of the balun in b2b configuration are compared to those extracted from full-wave simulation of the structure. A good agreement of the characteristics of the two curves can be noticed, although their levels differ by about a few dB for $|S_{11}|$ and fractions of dB for $|S_{21}|$.



(a) (b)

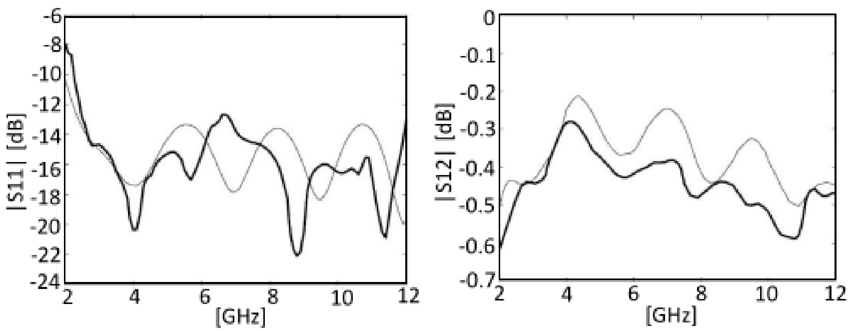
Figure 6. The photos of baluns in b2b configurations: straightway and by quarter-wave line according to [14], (a) top view, (b) bottom view.



(a) (b)

Figure 7. Scattering parameters S_{11} and S_{21} of the prototype extracted from measurements data (thick line) compared to extracted from numerical model (thin line).

The baluns on RT Duroid 6006 (current project) was next designed and fabricated in b2b configurations, and the scattering parameters were extracted from results of measurements. The $|S_{11}|$ and $|S_{21}|$ characteristics are shown in Fig. 8 and compared to those extracted from full-wave simulations of b2b baluns configuration.



(a) (b)

Figure 8. Scattering parameters $|S_{11}|$ and $|S_{21}|$ of the current project extracted from measurements data (thick line) compared to extracted from numerical model (thin line).

The agreement between measured and simulated curves is not so good as in the case of the prototype especially for the reflection coefficient characteristic. However, the maximum values of $|S_{11}|$ are similar for simulated and measured values. The characteristics of $|S_{21}|$ obtained from simulation and measurements are similar, and they differ by fractions of dB.

It is worthwhile to mention that the proposed design procedure has been verified for other types of the baluns for different substrates as well as for different operation frequencies [7].

7. CONCLUSION

Multistep design procedure for microstrip UWB balun is proposed in which the approximate dimensions of current project are found by scaling the dimensions of prototype. This approximate design is next corrected by ANN which is learned by the results of full-wave simulations. Design procedure was verified for the case of UWB balun with radial stub. Theoretical scattering parameters were compared to the experimental data obtained from measurements of fabricated baluns in back-to-back configurations. Generally, the numerical efficiency of the proposed procedure increases with the number of the designs made for given layout and different substrates. As a result, it is recommended, e.g., for studies of sensitivity of balun parameters to the stochastic changes of the parameters of substrates.

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REFERENCES

1. Koziel, S., J. W. Bandler, and W. Madsen, "A space mapping framework for engineering optimization: Theory and implementation," *IEEE Trans. Microw. Theory Tech.*, Vol. 54, No. 10, 3721–3730, Oct. 2006.
2. Koziel, S., S. Ogurtsov, W. Zieniutycz, and A. Bekasiewicz, "Design of a planar UWB dipole antenna with an integrated balun using surrogate-based optimization," *IEEE Antennas and Wireless Propagation Letters*, Vol. 14, 366–369, 2015.

3. Zhang, Q. J., K. C. Gupta, and V. K. Devabhaktuni, "Artificial neural networks for rf and microwave design — From theory to practice," *IEEE Trans. Microw. Theory Tech.*, Vol. 51, No. 4, 1339–1350, 2003.
4. Cao, Y., S. Reitzinger, and Q. J. Zhang, "Simple and efficient high-dimensional parametric modeling for microwave cavity filters using modular neural network," *IEEE Microwave and Wireless Components Letters*, Vol. 21, No. 5, 258–260, 2011.
5. Gibbings, J. C., *Dimensional Analysis*, Springer-Verlag, Londyn, UK, 2011.
6. Hart, G. W., *Multidimensional Analysis*, Springer-Verlag, Nowy Jork, USA, 1995.
7. Sorokosz, L. and W. Zieniutycz, "Electromagnetic modeling of microstrip elements aided with artificial neural network," *2020 Baltic URSI Symposium (URSI)*, 85–88, 2020.
8. Pozar, D. M., *Microwave Engineering*, John Wiley & Sons, 1998.
9. Wadell, B. C., *Transmission Line Design Handbook*, Artech House, Boston, USA, 1991.
10. Sorokosz, L., "Microwave baluns design with use of electromagnetic modeling and the aid of artificial neural networks," PhD Dissertation, Gdansk University of Technology, 2016 (in Polish).
11. Gunel, T. and S. Kent, "Numerical modeling of microwave radial stub," *Journal of Microwave Power and Electromagnetic Energy*, Vol. 32, No. 4, 246–250, 1997.
12. Suh, Y. and K. Chang, "A wideband coplanar stripline to microstrip transition," *IEEE Microwave and Wireless Components Letters*, Vol. 11, No. 1, 28–29, 2001.
13. Beachkofski, B. K. and R. V. Grandhi, "Improved distributed hypercube sampling," *43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 22–25, Denver, USA, Apr. 2002.
14. Sorokosz, L. and W. Zieniutycz, "Estimation of a single balun parameters on the base of back-to-back measurements," *21st Int. Conf. on Microwave, Radar and Wireless Communications (MIKON)*, 2016.