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ADAPTIVE NEURO-FUZZY MODELS FOR CONVENTIONAL COPLANAR WAVEGUIDES

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Abstract—In this work a new method based on the adaptive neuro-fuzzy inference system (ANFIS) was successfully introduced to determine the characteristic parameters, effective permittivities and characteristic impedances, of conventional coplanar waveguides. The ANFIS has the advantages of expert knowledge of fuzzy inference system and learning capability of neural networks. A hybrid-learning algorithm, which combines least-square method and backpropagation algorithm, is used to identify the parameters of ANFIS. There are very good agreement between the results of ANFIS models, experimental works, conformal mapping technique, spectral domain approach and a commercial electromagnetic simulator, MMICTL.

1. INTRODUCTION

Advances in monolithic microwave integrated circuit (MMIC) technology and progress in computer-aided design (CAD) tools have led the researchers to develop CAD models for the analysis and synthesis of the generic transmission lines. CPWs are ideally suited for modern microwave integrated circuit (MIC) as well as MMIC applications and high-speed integrated circuits. They have been the most studied transmission lines because of their planar structures [1–14] since first introduced by Wen [5]. The principal of a CPW is that the locations of signal grounds are on the same substrate surface as the signal line. This eliminates the need for via holes and thus simplifies the fabrication process. CPW circuits can be made denser than conventional microstrip circuits and have been employed in many practical RF circuit designs and also as a feed for excitation of microstrip antennas. These, and several other advantages, make CPWs ideally suited for MIC as well as MMIC applications. They are often used in designing power dividers, balanced mixers, couplers and filters. The various CPWs have been analyzed recently by many investigators using quasi-static methods [1–6] or full-wave methods [7–14]. While full-wave methods are the most accurate tools for obtaining the transmission line characteristics and analytically extensive, quasi-static methods are quite simple but do not threaten the dispersive nature of generic transmission lines. Consequently, the approximation of the quasi-static methods becomes worse as the transmission line becomes dispersive. However, as in the dispersion analysis of transmission lines presented by Knorr and Kuchler [10], CPW parameters are only slightly sensitive to variations of the frequency for CPWs with dimensions not exceeding the substrate thickness for nearly the whole microwave region. That is why quasi-static methods provide simulation accuracy comparable with full-wave methods for frequency up to 20 GHz [10].

As mentioned above, the methods used to obtain the characteristic parameters of CPWs have some drawbacks. Full-wave methods mainly take tremendous computational efforts, can not still make a practical circuit design feasible within a reasonable period of time, and require strong mathematical background knowledge and time-consuming numerical calculations. So they are not very attractive for the interactive CAD models. On the other hand, closed-form design equations obtained by conformal mapping technique (CMT), which is the simplest and most often used quasi-static method, consist of complete elliptic integrals. For this reason, the approximate formulas are proposed in the calculation of elliptic integrals [15]. CMT and other quasi-static methods require also strong background knowledge.

In this work, an alternative method based on the ANFIS [16–20] is presented to calculate the characteristic parameters, the effective permittivities and characteristic impedances, of conventional CPWs (CCPWs). The ANFIS is a fuzzy inference system (FIS) implemented in the framework of an adaptive fuzzy neural network. It combines the benefits of artificial neural networks (ANNs) and FISs in a single model. Fast and accurate learning, excellent explanation facilities in the form of semantically meaningful fuzzy rules, the ability to accommodate both data and existing expert knowledge about the problem, and good generalization capability features have made neuro-fuzzy systems popular in the last few years [21, 22]. In [21], ANFIS was successfully introduced by Guney et al. to compute the input resistance of rectangular microstrip antennas (MSAs). In [22], Rahouyi et al. have been successfully applied this technique to a microwave tunable phase shifter. This modeling technique is relatively new to the microwave engineering. So, in this work the ANFIS modeling technique is introduced to determine the characteristic parameters of CCPWs. In the following sections, the process of the determination of the characteristic parameters of CCPWs and ANFIS are described briefly, and then the application of ANFIS to the calculation of characteristic parameters of CCPWs is explained.

2. DETERMINATION OF CHARACTERISTIC PARAMETERS OF CPWs

The cross-section of a CCPW is depicted in Figure 1. In this figure, the central strip width is represented by S, the distance of separation between two semi-infinite ground planes is illustrated by d, and consequently the slot width is given by w. On the other hand, h indicates the thickness of the dielectric material with relative permittivity ε_r.

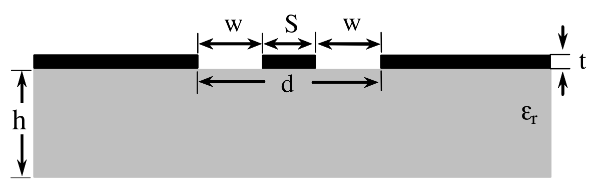


Figure 1. Cross-section of a CCPW.

In quasi-static analysis, all conductor materials assumed that perfectly conducting and the thickness of the conductors (t) are ignored. The characteristic parameters of CCPWs can be determined when the total capacitance and air capacitance per unit length of CCPWs are known. The total capacitance of CCPW is the sum of air and partial capacitances. Using the quasi-static approximations, effective permittivity (ε_{eff}) and characteristic impedance (Z_0) are:

$$\varepsilon_{eff} = \frac{C}{C_0} \tag{1}$$

$$Z_0 = \frac{1}{v_0 \cdot C_0 \cdot \sqrt{\varepsilon_{eff}}} \tag{2}$$

where v_0 is the speed of light in free space, C is the total capacitance of the transmission line, C_0 is the air capacitance of the corresponding line when all dielectrics are replaced by air. Therefore, in order to obtain the characteristic parameters of CCPW one only has to find the capacitances of C and C_0. Thus, the total capacitance of the transmission line is

$$C = C_0 + C_1 \tag{3}$$

where C_1 is partial capacitance. After a sequence of several conformal mapping steps applied to the original structure of a CCPW, the air and partial capacitances C_0 and C_1 are obtained as described in [3];

$$C_0 = 4 \cdot \varepsilon_0 \cdot \frac{K(k_0)}{K(k_0')} \tag{4}$$

$$C_1 = 2 \cdot (\varepsilon_r - 1) \cdot \varepsilon_0 \cdot \frac{K(k_1)}{K(k_1')} \tag{5}$$

where $K(k_i)$ and $K(k_i')$ are the complete elliptic integrals of the first kind with the modulus

$$k_0 = \frac{S}{S + 2 \cdot w} \tag{6}$$

$$k_1 = \frac{\sinh\left(\frac{\pi \cdot S}{4 \cdot h}\right)}{\sinh\left(\frac{\pi \cdot d}{4 \cdot h}\right)} \tag{7}$$

and the complementary modulus

$$k_i' = \sqrt{1 - k_i^2} \tag{8}$$

The effective permittivity of CCPW can be determined by substituting Eqs. (4)–(8) into Eq. (1) as

$$\varepsilon_{\mathit{eff}} = 1 + q_1 \cdot (\varepsilon_r - 1) \tag{9}$$

where q_1 is partial filling factor;

$$q_1 = \frac{1}{2} \frac{K(k_1)}{K(k_1')} \cdot \frac{K(k_0')}{K(k_0)} \tag{10}$$

and the characteristic impedance (Z_0) can be then determined by substituting Eqs. (4) and (9) into Eq. (2) as

$$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_{\mathit{eff}}}} \cdot \frac{K(k_0')}{K(k_0)} \tag{11}$$

Finally, $\varepsilon_{\mathit{eff}}$ and Z_0 are achieved for CCPWs. These closed-form expressions obtained by CMT consist of complete elliptic integrals of the first kind. Approximate formulas were proposed for calculation of the elliptic integrals [15].

In this work, effective permittivities and characteristic impedances of CCPWs are easily and simply determined by ANFIS models. The inputs to ANFIS models are the relative permittivity of the dielectric material, and two different geometrical dimensions, d/h and S/d, of CCPWs. The output of the model is $\varepsilon_{\mathit{eff}}$ or Z_0 of CCPWs.

3. ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM

ANFIS is a FIS implemented in the framework of an adaptive fuzzy neural network, and is a very powerful approach for building complex and nonlinear relationship between a set of input and output data [16, 17]. It combines the explicit knowledge representation of FIS with the learning power of ANNs. Usually, the transformation of human knowledge into a fuzzy system (in the form of rules and membership functions) does not give exactly the target response. So, the optimum values of the FIS parameters should be found. The main objective of the ANFIS is to determine the optimum values of the equivalent FIS parameters by applying a learning algorithm using input-output data sets. The parameter optimization is done in such a way that the error between target and actual output is minimized.

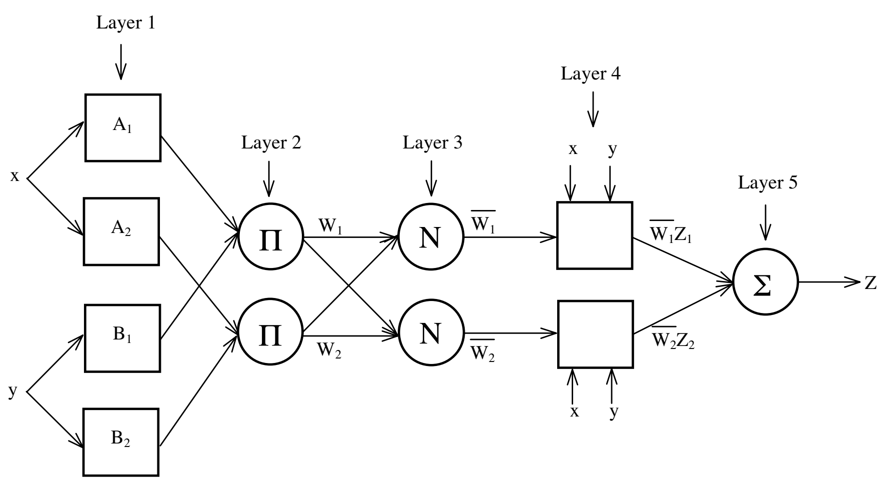


Figure 2. Architecture of ANFIS.

ANFIS architecture consists of fuzzy layer, product layer, normalized layer, de-fuzzy layer, and summation layer. A typical ANFIS architecture is shown in Figure 2, in which a circle indicates a fixed node, whereas a square indicates an adaptive node. For simplicity, we assume that the FIS under consideration has two inputs x and y and one output z. The ANFIS used in this work implements a first-order Sugeno fuzzy model. Among many FIS models, the Sugeno fuzzy model is the most widely applied one for its high interpretability and computational efficiency, and built-in optimal and adaptive techniques. For a first-order Sugeno fuzzy model, a common rule set with two fuzzy if-then rules can be expressed as

$$\text{Rule 1: If } x \text{ is } A_1 \text{ and } y \text{ is } B_1\text{, then } z_1 = p_1x + q_1y + r_1 \quad (12)$$

$$\text{Rule 2: If } x \text{ is } A_2 \text{ and } y \text{ is } B_2\text{, then } z_2 = p_2x + q_2y + r_2 \quad (13)$$

where A_i and B_i are the fuzzy sets in the antecedent, and p_i, q_i, and r_i are the design parameters that are determined during the training process. As in Figure 2, the ANFIS consists of five layers:

Layer 1: Every node i in this layer is an adaptive node with a node function:

$$Q_i^1 = \mu_{A_i}(x), \quad i = 1, 2 \quad (14)$$

$$Q_i^1 = \mu_{B_{i-2}}(y), \quad i = 3, 4 \quad (15)$$

where x (or y) is the input of node i. $\mu_{A_i}(x)$ and $\mu_{B_{i-2}}(y)$ can adopt any fuzzy membership function (MF). In general, the types of MFs are determined by trial-and-error method and/or operator's experience. After this determination, the parameters of MFs and the number of fuzzy rules can be optimally obtained by using optimization techniques. In this paper, the following generalized bell and Gaussian MFs are used.

$$bell(x; a_i, b_i, c_i) = \frac{1}{1 + \left|\dfrac{x - c_i}{a_i}\right|^{2b_i}} \quad (16)$$

$$Gaussian\,(x;\, c,\, \sigma) = e^{-\frac{1}{2}\cdot\left(\frac{x-c}{\sigma}\right)^2} \quad (17)$$

where $\{a_i, b_i, c_i\}$ and $\{c,\, \sigma\}$ are the parameter set that changes the shapes of the MFs. Parameters in this layer are named as *the premise parameters.*

Layer 2: Every node in this layer is a fixed node labeled Π, which multiplies the incoming signals and outputs the product:

$$Q_i^2 = w_i = \mu_{A_i}(x) \cdot \mu_{B_i}(y), \quad i = 1, 2 \quad (18)$$

Each node output represents the firing strength of a rule.

Layer 3: Every node in this layer is a fixed node labeled N. The ith node calculates the ratio of the ith rule's firing strength to the sum of all rules' firing strengths:

$$Q_i^3 = \bar{w}_i = \frac{w_i}{w_1 + w_2}, \quad i = 1, 2 \quad (19)$$

where $\bar{w}_i$ is referred to as *the normalized firing strengths.*

Layer 4: Every node i in this layer is an adaptive node with a node function:

$$Q_i^4 = \bar{w}_i \cdot z_i = \bar{w}_i \cdot (p_i x + q_i y + r_i), \quad i = 1, 2 \tag{20}$$

where $\bar{w}_i$ is the output of layer 3, and $\{p_i, q_i, r_i\}$ is the parameter set. Parameters in this layer are referred to as *the consequent parameters.*

Layer 5: The single node in this layer is a fixed node labeled Σ, which computes the overall output as the summation of all incoming signals:

$$Q_1^5 = \sum_{i=1}^{2} \bar{w}_i \cdot z_i = \frac{w_1 \cdot z_1 + w_2 \cdot z_2}{w_1 + w_2} \tag{21}$$

It can be seen from the ANFIS architecture that when the values of premise parameters are fixed, the overall output can be expressed as a linear combination of the consequent parameters:

$$z = (\bar{w}_1 x)\, p_1 + (\bar{w}_1 y)\, q_1 + (\bar{w}_1)\, r_1 + (\bar{w}_2 x)\, p_2 + (\bar{w}_2 y)\, q_2 + (\bar{w}_2)\, r_2 \tag{22}$$

The optimal values of the consequent parameters can be found by using the least-mean-square. When the premise parameters are not fixed, the search space becomes larger and the convergence of training becomes slower. The hybrid learning (HL) algorithm combining the least-mean-square and backpropagation (BP) algorithm can be used to solve this problem. This algorithm converges much faster since it reduces the dimension of the search space of the BP algorithm. During the learning process, premise parameters in layer 1 and consequent parameters in layer 4 are tuned until the desired response of FIS is achieved.

The HL algorithm has a two-step process. First, while holding the premise parameters fixed, the functional signals are propagated forward to layer 4, where the consequent parameters are identified by the least-mean-square. Then, the consequent parameters are held fixed while the error signals, the derivative of the error measure with respect to each node output, are propagated from the output end to the input end, and the premise parameters are updated by the standard BP algorithm.

4. APPLICATION TO THE PROBLEM

ANFIS has been adapted for the calculation of the effective permittivity and characteristic impedance of CCPWs when the values of relative permittivity ε_r, the ratio of S/d, and the ratio of d/h are given. For the ANFIS, the inputs are ε_r, d/h and S/d, and the output is the effective permittivity or characteristic impedance of CCPWs. 5670 data sets have been used to train the ANFIS models. The ranges of training data sets are among $1 \leq \varepsilon_r \leq 21$, $0.1 \leq S/d \leq 0.9$ and $0.38 \leq d/h \leq 65$. 2941 data sets, which are completely different from training data set, were used for testing the models. The ANFIS model used in calculating the characteristic parameters of CCPWs is shown in Figure 3. Training an ANFIS with the use of the HL algorithm to compute the characteristic parameters of CCPWs involves presenting it sequentially with different sets (ε_r, d/h and S/d) and corresponding characteristic parameters (ε_{eff} or Z_0). Differences between the target outputs and the actual outputs of the ANFIS are evaluated by the HL algorithm. The adaptation is carried out after the presentation of each set (ε_r, d/h and S/d) until the calculation accuracy of the ANFIS is deemed satisfactory according to some criterion (for example, when the error between target and the actual output for all the training set falls below a given threshold) or when the maximum allowable number of epochs is reached. The training and test data sets used in this article have been obtained from previous numerical methods [3, 14], simulation [23] and experimental works [24–26] results. The number of epochs used for training was 150. The HL algorithm can dramatically reduce the required training epochs because the training errors are decoupled and treated separately.

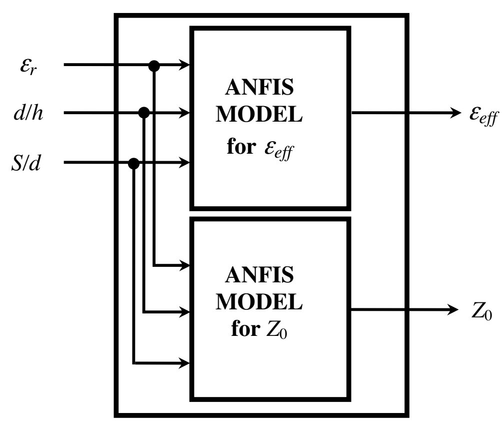


Figure 3. The structure of proposed ANFIS model.

The input and output data sets are scaled between 0 and 1 before training. The membership functions (MFs) for the input variables ε_r, d/h and S/d are the Gaussian, generalized bell, and Gaussian, respectively. The number of rules is then 24 ($3 \times 2 \times 4 = 24$). The types of MFs for the input variables are selected as the generalized bell.

It is clear from Eqs. (16) and (17) that the Gaussian and generalized bell MFs are specified by two and three parameters, respectively. Therefore, ANFIS used here contains a total of 116 fitting parameters, of which 20 ($3 \times 2 + 2 \times 3 + 4 \times 2 = 20$) are the premise parameters and 96 ($4 \times 24 = 96$) are the consequent parameters.

It is well known that ANFIS has one output. For this reason, in this paper two separate ANFISs with identical structure are used for calculating the effective permittivity and characteristic impedance. Although the number of inputs, input values, the number of MFs, and the types of MFs are the same for each ANFIS, the values of premise and consequent parameters for each ANFIS are different.

5. RESULTS AND CONCLUSION

The characteristic impedance test results obtained by using ANFIS model are compared with the results of the CMT [3] and the spectral domain approach (SDA) [14] in Table 1 for CCPWs with different geometrical dimensions and different dielectric materials. In order to make a further comparison, the characteristic impedances results obtained by a commercial simulator MMICTL [23] are also given in this table.

Table 1. Comparison of characteristic impedances Z_0 (Ω) obtained by using ANFIS model, CMT, SDA, and MMICTL for CCPWs ($h = 200\,\mu$m).

CPW Parameters \ Methods		Presented ANFIS model			CMT [3]			SDA [14] (f = 1.0 GHz)			MMICTL [23] (f = 1.0 GHz)		
S/d	d/h	$\varepsilon_r = 20$	$\varepsilon_r = 12.9$	$\varepsilon_r = 2.25$	$\varepsilon_r = 20$	$\varepsilon_r = 12.9$	$\varepsilon_r = 2.25$	$\varepsilon_r = 20$	$\varepsilon_r = 12.9$	$\varepsilon_r = 2.25$	$\varepsilon_r = 20$	$\varepsilon_r = 12.9$	$\varepsilon_r = 2.25$
0.2	0.5	57.20	68.45	140.35	54.49	67.95	140.75	55.76	68.28	141.4	55.23	67.86	140.01
	1.7	59.16	71.86	143.64	57.52	70.29	142.86	57.52	70.27	142.97	57.43	70.38	142.25
	2.3	60.28	73.59	145.18	59.00	72.13	144.83	59.02	71.95	143.95	58.90	72.04	143.28
	3.5	62.75	77.11	148.06	62.89	76.44	147.85	62.6	75.93	146.3	62.44	75.98	145.65
0.4	0.5	41.70	50.79	106.44	42.04	51.47	106.57	42.22	51.69	106.99	41.88	51.46	106.11
	1.7	44.61	54.42	109.17	43.88	53.60	108.47	43.86	53.56	108.32	43.86	53.73	108.1
	2.3	46.04	56.15	110.42	45.28	55.21	109.82	45.2	55.05	109.34	45.14	55.17	108.95
	3.5	48.82	59.48	112.76	48.46	58.82	112.62	48.24	58.44	111.41	48.12	58.49	110.94
0.6	0.5	31.88	39.40	84.05	33.32	40.8	84.45	33.48	40.99	84.83	33.23	40.82	84.15
	1.7	34.86	42.69	86.23	34.87	42.59	86.04	34.86	42.56	85.84	34.94	42.79	85.95
	2.3	36.24	44.21	87.24	35.99	43.87	87.12	35.93	43.76	86.68	35.93	43.9	86.54
	3.5	38.81	47.07	89.09	38.41	46.63	89.24	38.26	46.36	88.38	38.18	46.42	88.02
0.8	0.5	25.41	31.17	65.05	25.68	31.45	65.09	25.86	31.66	65.51	25.68	31.56	65.06
	1.7	26.96	32.99	66.40	26.81	32.75	66.03	26.8	32.71	66.03	27.07	33.16	66.69
	2.3	27.70	33.84	67.03	27.56	33.61	66.59	27.53	33.54	66.59	27.66	33.82	66.89

The full-wave simulator MMICTL uses a very general, rigorous numerical method, spectral operator expansion (SOE) technique (a fast, enhanced spectral domain method) to generate strip characteristics.

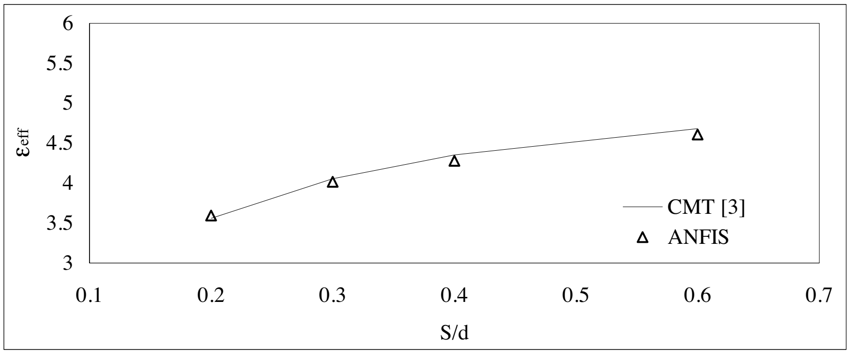
The average percentage errors (APEs) of the ANFIS model with respect to the other theoretical [3, 14] and electromagnetic simulator results [23] are listed in Table 2 for the characteristic impedances of CCPWs. It can be clearly seen from these tables that the results of ANFIS models are in very good agreement with the results of CMT [3], SDA [14] and MMICTL [23].

Table 2. The APEs of the ANFIS model with respect to the CMT, SDA, and MMICTL for the characteristic impedances of CCPWs.

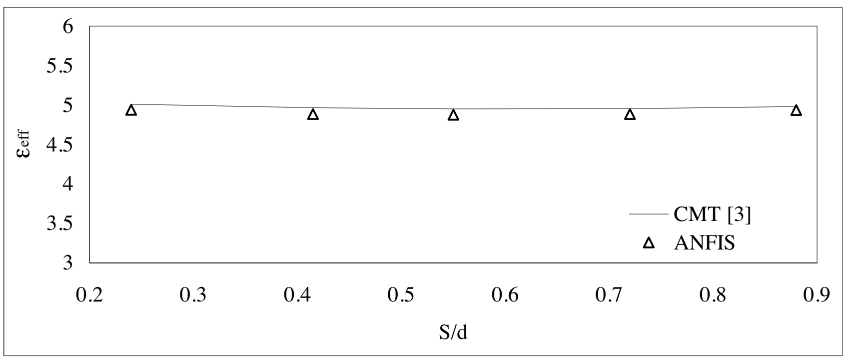
Methods	CCPWs $0.2 < S/d < 0.8$ and $0.5 < d/h < 3.5$		
	APEs		
	$\varepsilon_r = 20$	$\varepsilon_r = 12.9$	$\varepsilon_r = 2.25$
CMT [3]	1.08	1.12	0.67
MMICTL [23]	1.55	1.35	0.77
SDA [14]	1.05	1.11	0.69

The effective permittivity and characteristic impedance test results of ANFIS models for the CCPWs with different geometrical dimensions and different dielectric materials are compared with the results of CMT in Figure 4 and Figure 5, respectively. As it can be seen from these figures, the results of ANFIS models for both effective permittivity and characteristic impedance are in very good agreement with the results of CMT. This very good agreement confirms the validity of ANFIS models proposed in this work.

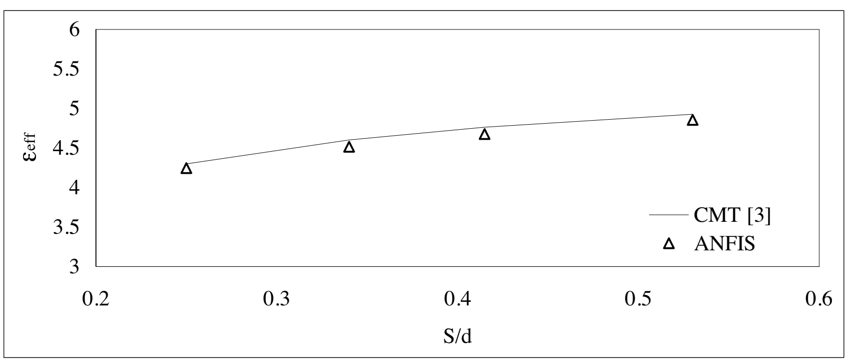
In order to further validate the presented method, the characteristic impedance test results of ANFIS model are compared with the MMICTL [23] and measured [24–26] results in Figure 5. It is clear from this figure that the ANFIS results agree quite well with the results of measured works and also with the results of MMICTL. There are small differences between the ANFIS model results and the experimental results. These differences are expected because it is assumed that the ground planes extend to infinity and the conductor thicknesses are zero for the ANFIS models, however, the CPW structures of the experimental works [24–26] have finite size ground planes in the range of 1270.0 μm and 3505.2 μm, and the



(a) S = 1270 μm, h = 1270 μm, and $\varepsilon_r = 9.2$

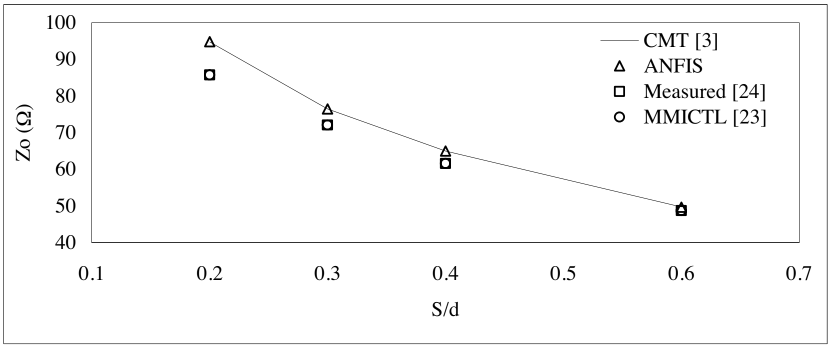


(b) d = 1000 μm, h = 640 μm, and $\varepsilon_r = 9.7$

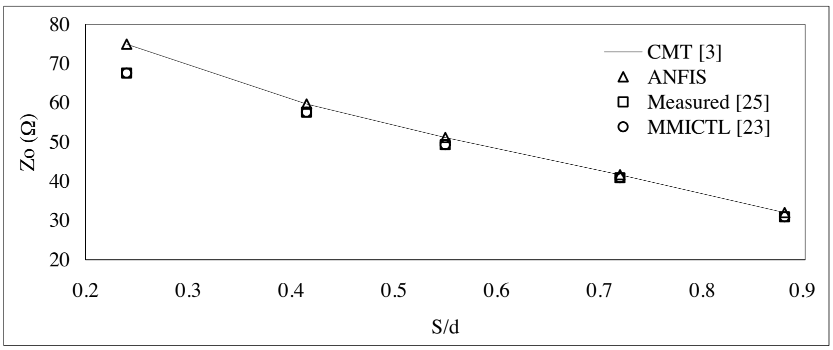


(c) S = 508 μm, h = 635 μm, and $\varepsilon_r = 9.6$

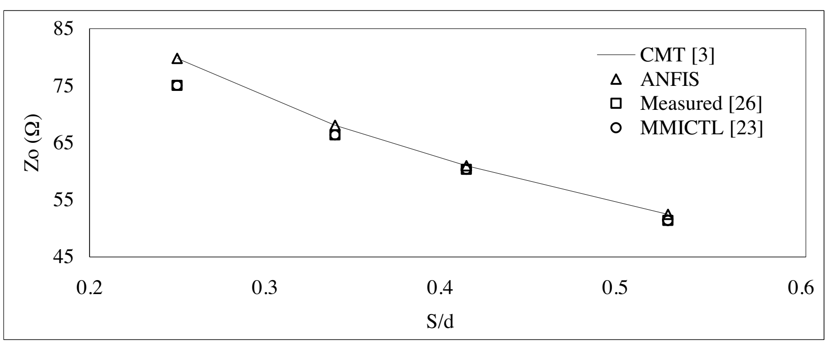
Figure 4. Comparison of the calculated effective permittivity values obtained by using ANFIS and CMT [3].



(a) $S = 1270$ μm, $h = 1270$ μm, and $\varepsilon_r = 9.2$



(b) $d = 1000$ μm, $h = 640$ μm,and $\varepsilon_r = 9.7$



(c) $S = 508$ μm, $h = 635$ μm, and $\varepsilon_r = 9.6$

Figure 5. Comparison of the measured and calculated characteristic impedances obtained by using ANFIS, CMT [3], and MMICTL [23] for CCPWs.

conductor thicknesses in the range of 1.8 μm and 15 μm.

As a consequence, the ANFIS models trained by the HL algorithm are presented to accurately calculate the effective permittivities and characteristic impedances of CCPWs. The proposed method is not limited to the calculation of the effective permittivities and characteristic impedances of CCPWs. This method can easily be applied to other microwave problems.

The ANFIS is a very powerful approach for building complex and nonlinear relationship between a set of input and output data. Accurate, fast, and reliable ANFIS models can be developed from measured/simulated microwave data. Once developed, these ANFIS models can be used in place of computationally intensive numerical models to speed up CPWs design. A distinct advantage of neural computation is that, after proper training, a neuro-fuzzy system completely bypasses the repeated use of complex iterative processes for new cases presented to it. It should also be emphasized that better results may be obtained from the ANFIS either by choosing different training and test data sets from the ones used in the paper or by supplying more input data set values for training.

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