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Modeling and Design of Anisotropic Circular Microstrip Patch Antenna Using Neurospectral Computation Approach

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***Abstract*—in this paper, we propose a general design of circular microstrip antenna printed on isotropic or anisotropic substrate, based on artificial neural networks (ANN) in conjunction with spectral domain formulation. In the design procedure, synthesis ANN model is used as feed forward network to determine the resonant characteristics. Analysis ANN model is used as the reversed of the problem to calculate the antenna dimension for the given resonant frequency, dielectric constant, and height of substrate. The effective parameters were combined with artificial neural network in the analysis and the design of circular antenna to reduce the complexity of the spectral approach and to minimize the CPU time necessary to obtain the numerical results. The results obtained from the neural models are in very good agreement with the experimental results available in the literature. Finally, numerical results of the anisotropy substrate effect on the resonant characteristics are also presented.**

Keywords—Circular Microstrip Antenna (CMSA), Artificial Neural Network (ANN), design and modeling, spectral domain approach, uniaxial anisotropy substrate.

I. INTRODUCTION

The microstrip antenna (MSA) is an excellent radiator for many applications such as mobile antenna, aircraft and ship antennas, remote sensing, missiles and satellite communications [1]. It consists of radiating elements (patches) photo etched on the dielectric substrate. Microstrip antennas are low profile conformal configurations. They are lightweight, simple and inexpensive, most suited for aerospace and mobile communication. Their low power handling capability posits these antennas better in low power transmission and receiving applications [2]. The flexibility of the Microstrip antenna to shape it in multiple ways, like square, rectangular, circular, elliptical, triangular shapes etc., is an added property. Various methods and commercial software are available for analysis and synthesis of microstrip antennas. These commercial design packages use computer intensive numerical methods such as, Finite Element Method (FEM), Method of Moment (MoM), Finite Difference Time Domain (FDTD) method, etc. These techniques require high computational resources and also take lot of computation time [3]. Even though all the losses can be directly included in the analysis, produced results may not provide satisfactory accuracy for all the cases. Because of these problems, Mishra and Patnaik have introduced the use of neural networks in conjunction with spectral domain approach to calculate the complex resonant frequency [4] and the input impedance [5] of rectangular microstrip resonators, this approach is named the neurospectral method. In reference [4], the computational complexity involved in finding complex root is reduced, whereas, in reference [5], the neural network method evaluates the integrals appearing in the matrix impedance. Later on [6], Mishra and Patnaik have demonstrated the force of the neurosperctal approach in patch antenna design by using the reverse modeling to determine the patch length for a given set of other parameters.

The increase in complexity of device modeling has led to rapid growth in the computational modeling research arena. To accommodate computational complexity, several computer aided design (CAD) modeling engines such as artificial neural networks (ANNs) were used [7-11]. ANNs, emulators of biological neural networks, have emerged as intelligent and powerful tools and have been widely used in signal processing, pattern recognition, and several other applications [9-10]. ANN is a massively parallel and distributed system traditionally used to solve problems of nonlinear computing [4, 12].

The objective of this work is to present an integrated approach based on artificial neural networks and electromagnetic knowledge (effective's parameters). We introduce the artificial neural networks in the analysis of circular antenna to reduce the complexity of the spectral approach and to minimize the CPU time necessary to obtain the numerical results. We have demonstrated the force of neurospectral approach in antenna modeling using ANN combined with EM knowledge to develop a neural network model for the calculation of resonant characteristics (resonant frequencies and bandwidths) of circular patch antenna printed

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on isotropic or uniaxially anisotropic substrate. Using reverse modeling, ANN is built to find out the antenna dimensions for the given resonant frequency, dielectric constant and height of substrate. The models are simple, easy to apply, and very useful for antenna engineers to predict both patch dimensions and resonant characteristics of circular microstrip antenna taken into account the anisotropy in the substrate. To the best of our knowledge, this subject has not been reported in the open literature; the only published results on analysis of rectangular microstrip-patch resonators using neurospectral approach [4-6].

II. Spectral Domain Formulation

As seen in Fig. 1, the circular microstrip antenna (CMSA) consists of a patch of radius a, which is parallel to the ground plane; and this patch is separated from the ground plane by a dielectric substrate with relative permittivity ε_r, and thickness h. If we want to take the substrate uniaxial anisotropy's into account, the number of inputs increases; since the relative dielectric permittivity ε_r will be replaced by the pair of relative permittivities (ε_x,ε_z), where ε_x and ε_z are the relative dielectric permittivity along x and z axis, respectively (Fig. 1).

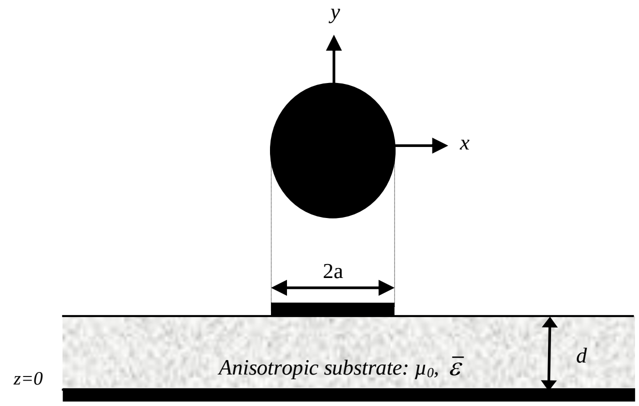

Fig. 1. Geometry of circular-disk microstrip antenna.

With the increase of design parameter's number, the network size increases, resulting in an increase in the size of training set required for proper generalization. Because of the different natures of the additional parameters, data generation becomes more complicated, a solution to this problem seems necessary. For the case of uniaxially anisotropic substrate, ε_{re} given in [13-14] there resulting values are:

$$\varepsilon_{re} = \varepsilon_z \quad (1)$$

$$d_e = d\sqrt{\frac{\varepsilon_x}{\varepsilon_z}} \quad (2)$$

In such an approach, the spectral function of Green, which binds the fields with the tangential electrical currents according to various plans of the drivers, must be given. Several techniques we proposed to evaluate the spectral Green function [14-15].

$$\mathbf{E}(\rho,\phi,z) = \begin{bmatrix} E_\rho(\rho,\phi,z) \\ E_\phi(\rho,\phi,z) \end{bmatrix} = \sum_{n=-\infty}^{n=+\infty} e^{in\phi} \int_0^\infty k_\rho dk_\rho\, \overline{\mathbf{H}}_n(\rho k_\rho) \cdot \mathbf{e}_n(k_\rho, z) \quad (3)$$

$$\mathbf{H}(\rho,\phi,z) = \begin{bmatrix} H_\phi(\rho,\phi,z) \\ -H_\rho(\rho,\phi,z) \end{bmatrix} = \sum_{n=-\infty}^{n=+\infty} e^{in\phi} \int_0^\infty k_\rho dk_\rho\, \overline{\mathbf{H}}_n(\rho k_\rho) \cdot \mathbf{h}_n(k_\rho, z) \quad (4)$$

$$\overline{\mathbf{H}}_n(\rho k_\rho) = \begin{bmatrix} J'_n(\rho k_\rho) & -\frac{in}{\rho k_\rho} J_n(\rho k_\rho) \\ \frac{in}{\rho k_\rho} J_n(\rho k_\rho) & J'_n(\rho k_\rho) \end{bmatrix} \quad (5)$$

In Eq. (5), $\overline{\mathbf{H}}_n(\rho k_\rho)$ is the kernel of the vector Hankel transform (VHT) [14-16], $J_n(.)$ is the Bessel function of the first kind of order n, and the prime denotes differentiation with respect to the argument. The dagger implies conjugate transpose.

The relationship which relates the current on the conducting patch to the tangential electric field in the corresponding interface:

$$\mathbf{e}_n(k_\rho, z) = \overline{\mathbf{G}}(k_\rho) \cdot \mathbf{K}_n(k_\rho) \quad (6)$$

Where $\overline{\mathbf{G}}(k_\rho)$ dyadic Green's function in the vector Hankel transform domain [16]. Note that in the vector Hankel transform domain, the dyadic Green's function is diagonal and it is independent of the geometry of the radiating patch.

Note that, the tensor of Green for the considered structure can be easily determined. The tangential electric field is null on the conducting patch, which leads to an integral equation. To solve the integral equation, we apply the procedure of Galerkin which consists in developing the unknown distribution of the current on the circular patch is expanded into a series of basis functions [14-16]. The basis functions chosen in this article for approximating the current density on the circular patch are obtained from the model of the cavity. Boundary conditions require that the transverse components of the electric field vanish on the perfectly conducting disk and the current vanishes off the disk, to give the following set of vector dual integral equations:

$$\mathbf{E}_n(\rho, z) = \int_0^{+\infty} dk_\rho k_\rho\, \overline{\mathbf{H}}_n(k_\rho \rho) \cdot \overline{\mathbf{G}}(k_\rho) \cdot \mathbf{k_n}(k_\rho) = \mathbf{0}, \qquad \rho < a \quad (7)$$

$$\mathbf{K}_n(\rho) = \int_0^{+\infty} dk_\rho k_\rho\, \overline{\mathbf{H}}_n(k_\rho \rho) \cdot \mathbf{k}_n(k_\rho) = \mathbf{0}, \qquad \rho > a \quad (8)$$

The use of the method of the moments in the spectral domain allows the resolution of the system of dual integral equations. The current on the disk is expressed in the form of a series of basis functions as follows:

$$\mathbf{K}_n(\rho)=\sum_{p=1}^{P} a_{np}\,\mathbf{\Psi}_{np}(\rho)+\sum_{q=1}^{Q} b_{nq}\,\mathbf{\Phi}_{nq}(\rho) \qquad (9)$$

P and *Q* correspond to the number of basis functions of $\mathbf{\Psi}_{np}(\rho)$ and $\mathbf{\Phi}_{nq}(\rho)$, respectively, a_{np} and b_{nq} are the mode expansion coefficients to be sought. The corresponding VHT of the current is given by

$$\tilde{\mathbf{K}}_n(k_\rho)=\sum_{p=1}^{P} a_{np}\,\tilde{\mathbf{\Psi}}_{np}(k_\rho)+\sum_{q=1}^{Q} b_{nq}\,\tilde{\mathbf{\Phi}}_{nq}(k_\rho) \qquad (10)$$

Substitute the current expansion (10) into (7). Next, multiplying the resulting equation by $\rho\mathbf{\Psi}^{+}{}_{nk}(\rho)$ (*k*=1,2..., *P*) and by $\rho\mathbf{\Phi}^{+}{}_{nl}(\rho)$ (*l*=1,2...,*Q*), and while integrating from 0 to *a*, and using the Parseval's theorem for vector Hankel transform [16], we obtain a system of linear *P*+*Q* algebraic equations for each mode n which can be written in the matrix form:

$$\overline{\mathbf{Z}}_n\,.\mathbf{C}_n=\mathbf{0} \qquad (11)$$

where:

$$\overline{\mathbf{Z}}_n=\begin{bmatrix}(\overline{\mathbf{Z}}_n{}^{\mathbf{\Psi\Psi}}{}_n)_{P\times P} & (\overline{\mathbf{Z}}_n{}^{\mathbf{\Psi\Phi}})_{P\times Q}\\ (\overline{\mathbf{Z}}_n{}^{\mathbf{\Phi\Psi}}{}_n)_{Q\times P} & (\overline{\mathbf{Z}}_n{}^{\Phi\Phi}{}_n)_{Q\times Q}\end{bmatrix},\quad \mathbf{C}_n=\begin{bmatrix}(\mathbf{a}_n)_{p\times 1}\\ (\mathbf{b}_n)_{q\times 1}\end{bmatrix} \qquad (12)$$

Each element of the submatrices is given by:

$$\overline{\mathbf{Z}}_n{}^{\mathbf{VW}}(i,j)=\int_0^{+\infty} dk\rho\,\mathbf{V}_{ni}^{+}(k_\rho)\cdot\overline{\mathbf{G}}(k_\rho)\cdot\mathbf{W}_{nj}(k_\rho) \qquad (13)$$

where **V** and **W** represent either **Ψ** or **Φ**. For every value of the integer n, the system of linear equations (11) has non-trivial solutions when

$$\det\left[\overline{\mathbf{Z}}_n(\omega)\right]=0 \qquad (14)$$

This equation (14) is called characteristic equation of the structure (figure. 1). For the search of the complex roots of this equation, the method of Müller is used. It requires three initial guesses which must be close if possible to the sought solution to ensure a fast convergence.

Generally the real part (f_r) of the solution represents the resonant frequency of the structure, the imaginary part (f_i) indicates the losses of energy per radiation and the ratio ($2f_i/f_r$) gives the band-width (*BW*) and the quantities $Q=(f_r/2f_i)$ stands for the quality factor [14-16].

In the following section, a basic artificial neural network is described briefly and the application of neural network to the prediction the resonant characteristics of the microstrip antenna are than explained.

III. Neural Network Modeling

ANN learns relationships among sets of input-output data which are characteristic of the device under consideration. It is a very powerful approach for building complex and nonlinear relationship between a set of input and output data [17].

Artificial neural networks (ANNs) have been used frequently in signal processing applications, speech and pattern recognition, remote sensing, etc. for the last two decades [18]. Ability, adaptive capability and ease of implementation have made ANN a popular tool for many design problems in today's communication world [19]. More importantly, ANNs can generalize and respond correctly to slightly deviant input values, not presented during the training process [20]. These networks directly give good approximation to simulated and measured value, thereby avoiding the need for possibly a more complex and time-consuming conventional problem-specific algorithm [19]. In the present scenario, neural network models are used extensively for wireless communication engineering, which eliminates the complex and time-consuming mathematical and simulation procedures for designing antennas [21-23].

Multilayer perceptrons have been applied successfully to solve some difficult and diverse problems by training them in a supervised manner with a highly popular algorithm known as the error back propagation algorithm [23].

As shown in Fig. 2, the MLP consists of an input layer, one or more hidden layers, and an output layer. Neurons in the input layer only act as buffers for distributing the input signals x_i to neurons in the hidden layer. Each neuron in the hidden layer sums its input signals x_i after weighting them with the strengths of the respective connections w_{ji} from the input layer and computes its output y_j as a function f of the sum, namely

$$y_j=f\left(\sum w_{ji}x_i\right) \qquad (15)$$

Where *f* can be a simple threshold function or a sigmoid or hyperbolic tangent function [24]. The output of neurons in the output layer is computed similarly.

Training of a network is accomplished through adjustment of the weights to give the desired response via the learning algorithms. An appropriate structure may still fail to give a better model unless the structure is trained by a suitable learning algorithm. A learning algorithm gives the change $\Delta w_{ji}(k)$ in the weight of a connection between neurons *i* and *j* at time *k*. The weights are then updated according to the formula

$$w_{ji}(k+1)=w_{ji}(k)+\Delta w_{ji}(k+1) \qquad (16)$$

MLP can be trained using many different learning algorithms [25]. In this article, the following back propagation learning algorithm described briefly was used to train the MLP.

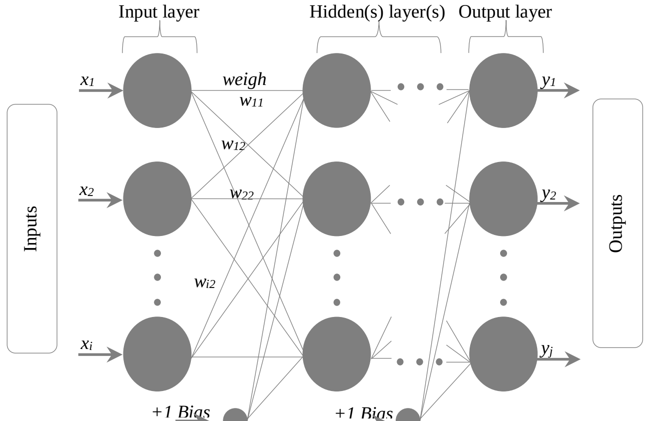

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Fig. 2. General form of multilayered perceptrons.

The back-propagation algorithm is based on the error correction learning rule. Basically, error back propagation learning consists of two passes through the different layers of the network, a forward pass and a backward pass. In the forward pass, an activity pattern is applied to the sensory nodes of the network, and its effect propagates through the network layer by layer [25]. Finally, a set of outputs is produced as the actual response of the network. During the forward pass the synaptic weights of the networks are all fixed. During the backward pass, on the other hand, all the synaptic weights are adjusted in accordance with an error correction rule. The actual response of the network is subtracted from a desired response to produce an error signal. This error signal is then propagated backward through the network against the direction of synaptic connections. The synaptic weights are adjusted to make the actual response of the network move closer to the desired response in a statistical sense [23]. ANN models accuracy depends on the amount of data presented to it during training. A well-distributed, accurately simulated or measured and sufficient data are the basic requirement to obtain an efficient model. All the numerical results presented in this paper we obtained on a Pentium IV computer with a 2.6-GHz processor and a total RAM memory of 2 GB.

In this work, the patch geometry of the microstrip antenna is obtained as a function of input variables, which are height of the dielectric material (d_e), dielectric constants of the substrate (ε_{re}), and the resonant frequency (f_r), using ANN techniques "Fig. 3". Similarly, in the analysis ANN, the resonant frequency of the antenna is obtained as a function of patch dimensions (a), height of the dielectric substrate (d_e), and dielectric constants of the material (ε_{re}) "Fig. 4". Thus, the forward and reverse sides of the problem will be defined for the circular patch geometry in the following subsections.

Synthesis of the patch geometry of the microstrip antenna is a problem for which closed-form solutions exist. Therefore, this example is very useful for illustrating features and capabilities of synthesis ANN. Details of the problem are presented next.

A. The forward side of the problem: The synthesis ANN

The input quantities to the ANN black-box in synthesis "Fig. 3" can be ordered as:

- d_e: height of the dielectric substrate;
- ε_{re}: effective dielectric substrate;
- f_r : resonant frequency of the antenna.

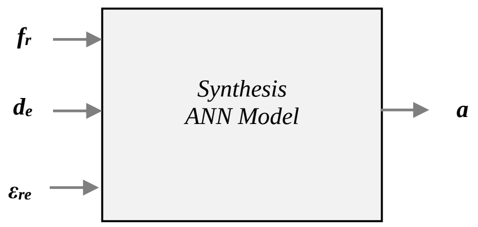

Fig. 3. Synthesis Neural model for predicting the patch geometry of circular microstrip antenna with effective parameters.

The following quantities can be obtained from the output of the black-box as functions of the input variables:

- a: radius of a circular patch;

B. The reverse side of the problem: The analysis ANN

In the analysis side of the problem, terminology similar to that in the synthesis mechanism is used, but the resonant frequency and the half-power bandwidth of the antenna are obtained from the output for a chosen dielectric substrate and patch dimensions at the input side as shown in "Fig. 4"

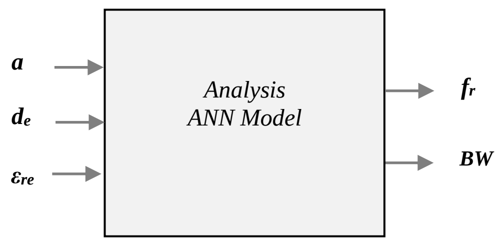

Fig. 4. Analysis Neural model for calculating the resonant frequency and half-power bandwidth of circular microstrip antenna with effective parameters.

The details of the network parameters for both these cases (analysis and synthesis) model are given in Table 1.

TABLE .1 COMPARISONS OF PERFORMANCE DETAILS OF ANALYSIS AND SYNTHESIS MODELS.

Algorithm details	**Neurospectral approach**	
	Analysis model	***Synthesis model***
Activation function	sigmoid	sigmoid
Training function (back-propagation)	trainrp	trainrp
Number of data	280	280
Number of neurons (input layer)	3	3
Number of neurons (hidden layers)	12-8	8-8
Number of neurons (output layer)	2	1
Epochs (number of iterations)	8000	8000
TPE (training performance error)	10^{-4}	10^{-4}
Time required	97 min	86 min
LR (learning rate)	0.6	0. 5
MC (momentum constant)	0.7	0.6

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IV. NUMERICAL RESULTS AND DISCUSSION

In order to confirm the computation accuracy of the neurospectral method, our results are compared with experimental and recent theoretical data [26-28].

Experimental and numerical evaluations have been performed with a patch for different radius *a*, printed on isotropic substrate ($\varepsilon_x=\varepsilon_z=2.43$) and thickness *d*=0.49mm. The Table 2 summarizes our computed resonant frequencies and those obtained for TM_{11} mode via spectral domain formulation [26-28]. The comparisons show a good agreement between our results and those of literature [26-28].

In the synthesis, neurospectral model give the best approximation to the target values. The results of the synthesis and comparison with targets are given in Table 3.

With the aim of confirming the computation accuracy for the case of uniaxially anisotropic substrate, we compare in Fig. 5 our results with theoretical data previously published [29].

TABLE 2. THEORETICAL AND EXPERIMENTAL VALUES OF THE RESONANT FREQUENCY FOR THE FUNDAMENTAL MODE OF CIRCULAR MICROSTRIP ANTENNA. $\varepsilon_x = \varepsilon_z = 2.43$, d= 0.49mm.

a (mm)	*a/d*	*Experiment (GHz) [26]*	*Computed (GHz)*			
			[26]	*[27]*	*[28]*	*Present*
1.9698	4.02	25.60	25.30	25.92	25.40	25.56
3.9592	8.08	13.10	13.30	13.55	13.30	13.18
5.8898	12.02	8.960	9.13	9.25	9.20	9.017
8.0017	16.33	6.810	6.80	6.87	---	6.823
9.9617	20.33	5.470	5.49	5.54	5.60	5.509

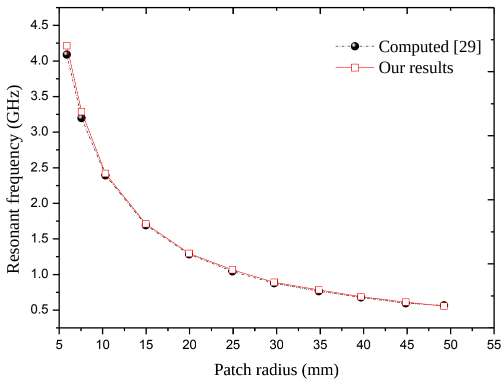


Fig. 5. Resonance frequency as a function of radius patch of a circular microstrip antenna on anisotropic substrate; Epsilam-10 $\left(\varepsilon_x = 13, \varepsilon_z = 10.3\right)$, *d=1.27*mm.

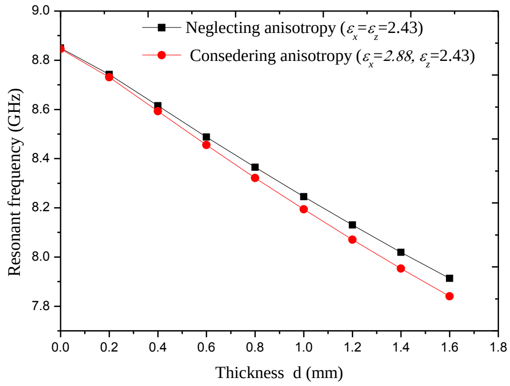
TABLE 3. REVERSE MODELING FOR THE PREDICTION OF ANTENNA DIMENSIONS.

Input parameters			**Target**	**ANN**
***d* (mm)**	$\varepsilon_x = \varepsilon_z$	***f_r* (GHz)**	***a*(mm)**	***a*(mm)**
1.588	2.5	1.57	34.93	34.967
3.175	2.5	1.51	34.93	34.930
2.35	4.55	0.825	49.5	49.583
2.35	4.55	1.03	39.75	39.634
2.35	4.55	2.003	20	20.076
2.35	4.55	3.75	10.4	10.415
2.35	4.55	4.945	7.7	7.695
1.5875	2.65	4.425	11.5	11.565
1.5875	2.65	4.723	10.7	10.622
1.5875	2.65	5.224	9.6	9.596
1.5875	2.65	6.074	8.2	8.185
1.5875	2.65	6.634	7.4	7.402

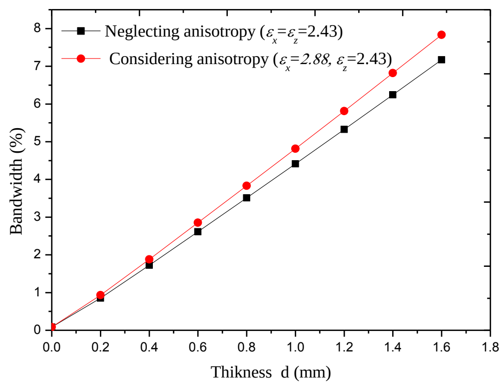
It is seen from figure .5 that our results are close to those given in [29]. This validates the proposed model for the case of anisotropic substrate.

In Figure 6, results are presented for the resonant frequency and bandwidth of circular microstrip patch printed on an anisotropic dielectric substrate (PTFE).

In this figure, the results obtained for the resonant frequency and bandwidth of patch on anisotropic PTFE ($\varepsilon_x = 2.88, \varepsilon_z = 2.43$) are compared with the results that would be obtained if the anisotropy of Boron nitride were neglected ($\varepsilon_x = \varepsilon_z = 2.43$). The patch has a radius of 6.35 mm.



(a)



(b)

Fig. 6. (a) Resonant frequency; (b) bandwidth of circular microstrip patch printed on anisotropic PTFE, the patch has a radius of 6.35mm.

The differences between the results obtained considering anisotropy and neglecting anisotropy reach 4.03 percent in the case of resonant frequencies and 32.34 percent in the case of half-power bandwidths. Thus, it can be concluded that the effect of uniaxial anisotropy on the resonant frequency and bandwidth of a circular microstrip patch antenna cannot be ignored and must be taken into account in the design stage.

V. Conclusion

A neural network-based CAD model can be developed for the analysis of a circular patch antenna printed on isotropic or anisotropic substrate, which is robust both from the angle of time of computation and accuracy. A distinct advantage of neuro-computing is that, after proper training, a neural network completely bypasses the repeated use of complex iterative processes for new cases presented to it. In the design procedure, syntheses ANN model is used as feed forward network to determine the resonant characteristics of circular microstrip antenna printed on anisotropic substrate. Analysis ANN model is used as the reversed of the problem to predict the antenna dimension for the given resonant frequency, dielectric constant and height of substrate. The spectral domain technique combined with the ANN method is several hundred times faster than the direct solution. This remarkable time gain makes the designing and training times negligible. Consequently, the Neurospectral method presented is a useful method that can be integrated into a CAD tool, for the analysis, design, and optimization of practical shielded (Monolithic microwave integrated circuit) MMIC devices.

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