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Design and Analysis of Ku/K-band Circular SIW Patch Antenna Using 3D EM-based Artificial Neural Networks

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Abstract

Substrate Integrated Waveguide (SIW) antennas are considered as main radiators for RF and microwave wireless systems due to their low profile, low cost and soft integration with the other devices. The gain of a SIW patch antenna may be enhanced using different techniques such as Artificial Neural Networks (ANN) by modifying the antenna's geometry with high efficiency comparing to electromagnetic techniques that take more time. This paper describes a novel structure of a circular SIW patch antenna design using a tree-dimensional electromagnetic (3D-EM) simulation based on ANN model which is developed as an accurate tool for synthesizing the forward side and then analyzing the reverse side of the problem. In this work, ANN algorithms are used for training the samples to provide precise geometrical dimensions of the SIW patch antenna with high accuracy for the target requirements. The antenna is designed to operate in Ku and K frequency bands, resonate at 16.10 GHz and 19.81 GHz respectively and show good performance resulting in low return losses of less than -10dB to -29dB for the selective frequency bands.

Keywords: *Substrate Integrated Waveguide (SIW), patch antennas, Ku/K bands, Artificial Neural Networks (ANN), 3D-EM simulation*

1. Introduction

As the growing expansion of RF and microwave applications operating at high frequencies motivates the development of effective technologies, SIW technology becomes very useful for designing circuits especially antennas by using periodic metallic via holes that largely preserves the well-known advantages of conventional rectangular waveguides, namely, high quality factor, high power capacity, and self-consistent electrical shielding, takes the advantages of microstrip lines, such as small volume, and light weight, and easily connects to other microstrip and coplanar components through simple transitions. This has consequently led to develop a variety of compact low-loss microwave integrated systems [1-3].

Recently, antennas employing SIW have achieved excellent radiation and good properties such as symmetry patterns, high gain, and very wide bandwidth, and their difficult modeling into planar forms due to the bulky geometry seems to become easier [4-5]. This has provided over the past decade an important class of microwave antennas with numerous wireless applications after using automatic modelling techniques to bring the Computer Aided Tuning (CAT) for such high frequency structures to its current state of the art. Artificial neural networks present one of the most popular automation techniques used for RF and microwave design optimization that consist of information processing systems with their design inspired by the studies of the ability of the human brain to learn from observations and to generalize by abstraction [6-7]. ANNs can be used to develop new models or enhance the accuracy of existing models. They learn device data through an automated training process, and the trained neural networks are then used as fast and accurate models for efficient high-level design.

In this paper, a novel design of a circular SIW patch antenna using High Frequency Structure Simulator (HFSS) is proposed for Ku (12-18GHz) and K (18-27GHz) band applications. The SIW patch antenna structure adopts two main parts: a tulip-shaped patch [8] and microstrip feeding line. The antenna parameters are optimized by developing an MATLAB based ANN algorithms trained by the back-propagation technique as a fitness function for excellent learning and accurate designing of the antenna's geometry. ANN Algorithms are trained by a set of existent input and output relations obtained by simulation to test data for the

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algorithms and analyze the SIW patch antenna parameters for the selective bandwidth. The design is then validated by comparing the ANN responses with input values provided for the combinations of dimension values, within the parameter range of the test set.

2. Circular SIW Patch Antenna Design

SIW geometry structure as shown in Figure 1 is composed of walls presented by two rows of metalized via holes with center-to-center distance called W_{SIW} embedded into a dielectric substrate and by the top and the bottom metallization of the dielectric substrate. The structure can be modeled by a conventional rectangular waveguide mainly defined by its horizontal length *a*, vertical length *b* designed to determine the guide's cut-off frequency and modes of excitation. The design parameters of the SIW are mainly defined by the set of valid relations [9] of a high performance and accurate modelling technique used mostly for calculating complex propagation constants of the substrate integrated waveguide, using the concept of surface impedance in modelling the rows of conducting cylinders:

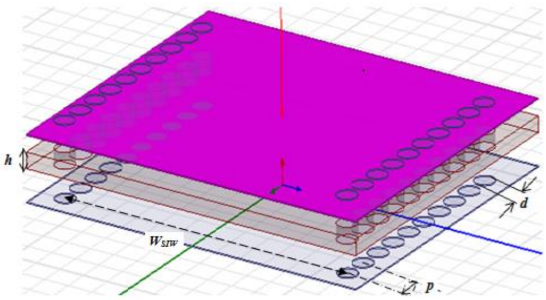


Figure 1. Substrate integrated waveguide structure

$$\begin{cases} d \leq \lambda_g / 5 \\ p \leq 2d \\ \dfrac{d}{a} \leq 0.4 \end{cases} \tag{1}$$

Where *p* is the centre distance between the via-holes, and d is the diameter of each via hole.

Practically, a SIW structure can be synthesized in a planar substrate form with arrays of metallic vias used to realize a bilateral edge of walls in which the SIW width (W_{SIW}) should be instead of a normalized equivalent width called W_{eq} given by the followed experimental formula [9-10]:

$$W_{eq} = W_{SIW}\left(\varepsilon_1 + \frac{\varepsilon_2}{\dfrac{p}{d} + \dfrac{\varepsilon_1 + \varepsilon_2 - \varepsilon_3}{\varepsilon_3 - \varepsilon_1}}\right) \tag{2}$$

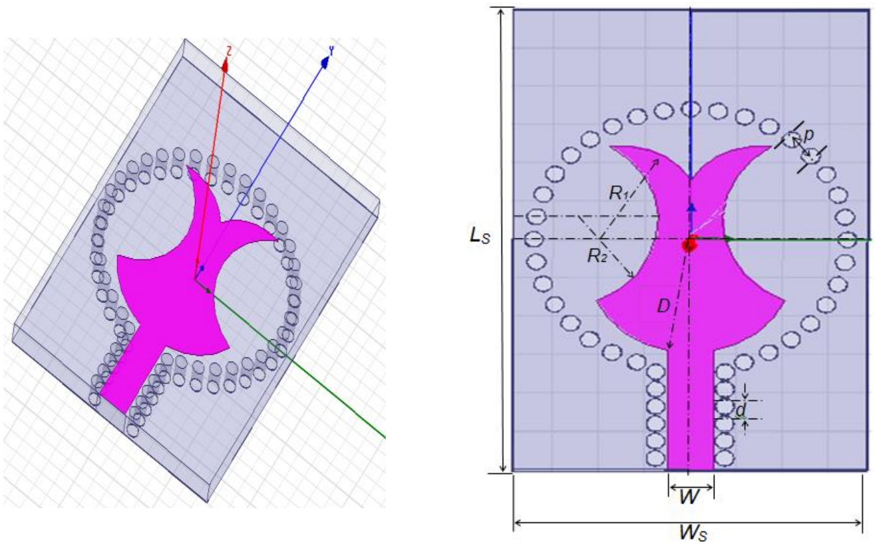
With:

$$\varepsilon_1 = 1.0198 + \left(\frac{0.3465}{\dfrac{a.p}{d} - 1.0684}\right) \quad \varepsilon_2 = -0.1183 - \left(\frac{0.9163}{\dfrac{a.p}{d} - 1.2010}\right) \quad \varepsilon_3 = -1.0082 - \left(\frac{1.2729}{\dfrac{a.p}{d} + 10.2052}\right) \tag{3}$$

Accordingly, a set of antenna geometric specifications is proposed for the analysis and optimization by calculating the SIW parameters basing on equations mentioned above, and using HFSS-based Eigen mode solution to determine the remaining antenna parameters including both microstrip line and tulip-shaped patch parameters. Details of geometric configuration of the circular SIW patch antenna proposed for the study are illustrated in Table 1 and Figure 2. *W*, *D*, R_1, R_2 present main antenna parameters to be optimized over Ku and K-bands of frequency by training an ANNs model to support both antenna's resonate frequencies and return losses, and validate Ku and K range operations.

Table 1. Circular SIW Patch Antenna Specifications

		Parameters (*mm*)		
		Substrate		
Longer (L_S)	Width (W_S)	Thickness (*h*)	Dielectric constant (ε_r)	Tangent loss (δ)
24	15.4	0.95	3.2	0.0018
		Microstrip line		
	Width (*W*)		2	
		SIW		
	Diameter(*d*)		Walls Center-to-center distance (*p*)	
	0.6		0.8	
		Tulip-shaped patch		
Diameter (*D*)		Inner ray (R_1)		Outer ray (R_2)
4.6		3.9		4.6



(a) (b)

Figure 2. Front view of (a) upper and (b) bottom metal face of the proposed circular SIW patch antenna

3. Artificial Neural Network Modelling of Circular SIW Patch Antenna

Geometrical parameters of the proposed circular SIW patch antenna have been optimized by introducing an ANN model using MATLAB programming in order to enhance the accuracy of the existing structure through an automated data training process having the ability to capture multidimensional arbitrary nonlinear relationships in a very fast way to finally provide an efficient high-level antenna design.

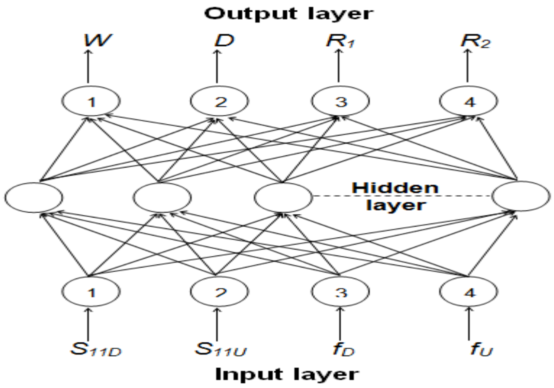


Figure 3. MLP-ANN architecture selected for the optimization

In this work, a Multilayer Perceptron (MLP) network structure has been adopted for the calculation of the resonant frequencies and return losses using for training standard, back propagation algorithms [11-12], in which neurons are grouped into three layers divided into: first layer which consists of input neurons, output layer which contains the output neurons, and remaining layer presenting the hidden layer. Figure 3 illustrates the MLP-ANN architecture used for the simulation and optimization. For the considered circular SIW patch antenna the developed neural model is designed to produce output parameters divided into D, R_1, R_2, and W, having down return loss S_{11D}, high return loss S_{11U}, down resonance frequency f_D and upper resonance frequency f_D as inputs. The range of inputs for training data and modelling problem are gathered in the Table 2.

Table 2. Training Data Range of Circular SIW Patch Antenna

Parameters	Training data range
W	2.0–2.4 mm
D	4.2-5.2 mm
R_1	3.2-4.2 mm
R_2	4.2–5.2 mm
f_D	15.5–17.5 GHz
f_U	19–20 GHz
S_{11D}	(-22)–(-18) dB
S_{11U}	(-32)–(-28) dB

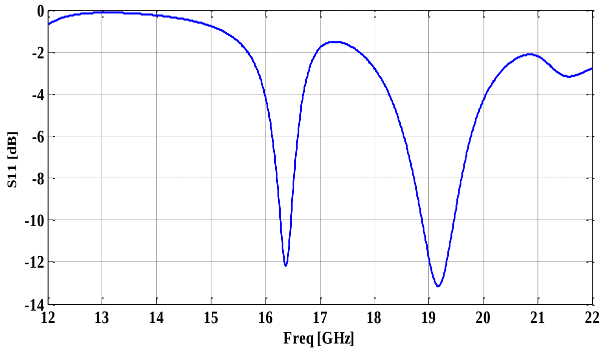
After having defined the antenna's input and output variables as a first stage known as neurons process, training data are generated using multi-HFSS simulations to provide a neural network model that will be incorporated into the simulator again for fast and accurate optimization as a second stage of the overall device called network training process. Likewise, the training error is automatically calculated, and network weights are being updated after each cycle in order to minimize the training error. The aim of the network training process is then to teach the network to produce valid response for inputs from outside the training data that is simply called generalization [13].

4. Optimization Results

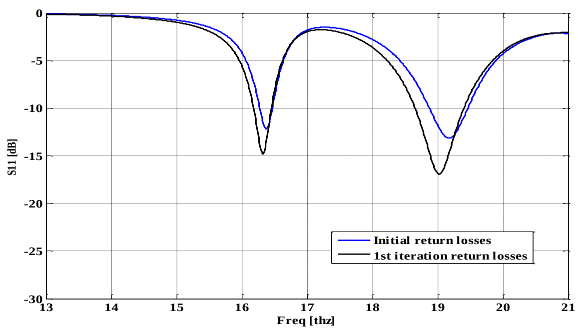
Figure 4 shows the simulated return losses of the proposed antenna design for Ku and K frequency bands. It is clearly observed that the selected geometric parameters have not presented a good performance in terms of low return losses. These parameters are then optimized through developing an accurate ANN model. Circular SIW patch antenna's parameters outputted by trained artificial neural network have been implemented by HFSS electromagnetic software to compare antenna responses with those initially provided. Both of these results are shown in Figure 5 from (a) to (d).

The results of optimization show that the antenna structure comes with very low return losses over the entire bands of resonance. The antenna has been found to resonate at 16.10

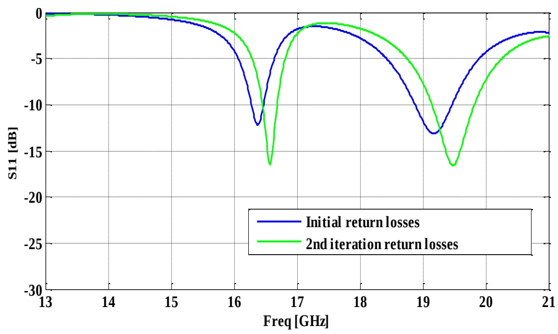
GHz with a return loss of -19.74dB and also at 19.81 GHz with a return loss of -29.54dB as shown in Figure 5-d. The results obtained from testing samples in ANN model are very useful for obtaining at resonance bands of the proposed circular SIW patch antenna, very low return losses.



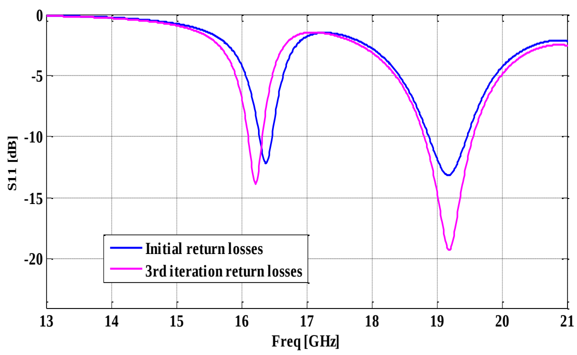
Initial parameters (mm): W=2.2, D=4.4, R_1=3.6, R_2=4.4
Figure 4. Return loss graph in dual-band Ku/K bands of the circular SIW patch antenna (before optimization)



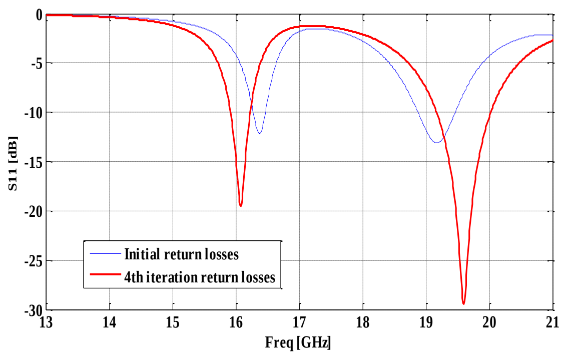
(a) 1st iteration, ANN Output parameters (mm): W=2.0152, D=4.6050, R1=3.9011, R2=4.6041



(b) 2nd iteration, ANN Output parameters (mm): W=2.2017, D=4.7393, R1=4.3348, R2=4.8440



(c) 3rd iteration ANN Output parameters (mm): W=2.1800, D=4.6814, R1=3.9634, R2=4.6923



(d) 4th iteration, ANN Output parameters (mm): W=2.3431, D=4.3434, R1=3.3903, R2=4.6785

Figure 5. Return loss graph in dual-band Ku/K bands of the optimized circular SIW patch antenna based on ANN modelling

This indicates that ANN model selected for the optimization offers the advantage of superior computational ability to provide an optimal circular SIW patch antenna geometry due to its high degree of efficiency and interconnectivity for solving complex problems. Table 3 shows the final geometric configuration reported from the fourth iteration proposed for the circular SIW patch antenna design after optimization.

Table 3. Optimized Circular SIW Patch Antenna Parameters

Optimized parameters	Values (*mm*)
W	2.3430
D	4.3434
R_1	3.3903
R_2	4.6785

5. Conclusion

In this paper, a novel circular SIW patch antenna design fed by a microstrip line is proposed for Ku and K band applications by developing an accurate MLP-ANN model and carrying out multiple HFSS simulations to achieve best approximations to target parameters providing a high structure precision as well as high performance level. Greater than -19dB and -29dB return losses at approximately 16.10 GHz and 19.81 GHz resonance frequencies have been obtained to be excellent characteristics for the proposed antenna design to operate in Ku and K bands of frequencies. MPL-ANN model selected for the optimization offers the advantage of superior computational ability to provide an optimal circular SIW patch antenna geometry due to its high accordance with user’s setting resonance frequencies and return losses.

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