
ANN Modeling of Microstrip Hairpin-Line Bandpass Filter

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Abstract

In this paper a design technique for Hairpin-Line narrow band Microstrip Bandpass filters is presented by using the artificial neural network (ANN) modeling method at mid-band frequency 2.2 GHz for S-band applications which give minimum insertion loss (S₂₁) of 0.2954 dB and maximum return loss of 27.4 dB in the passband. Consequently an artificial neural network model is developed to observe the Magnitude variation of scattering parameters (S-parameters) of Microstrip Band-pass filters at 2.2 GHz for different dimensions. The developed ANN model of microstrip band-pass filter is computationally more efficient in the design and the results are more accurate as compared to an Electromagnetic simulator. Essential dimensions of the microstrip filter layout are used to obtain the input-output relationships in the ANN model. The simulation and ANN training is performed using the commercial electromagnetic simulation software Zeland IE3D 14.1 and MATLAB programming language respectively.

Keywords

Microstrip Hairpin-Line Bandpass Filters, Coupling Coefficient, ANN model, MATLAB, IE3D EM Simulation, S-parameters, Training Algorithm.

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Introduction

In microwave and satellite communication, compact and highly efficient bandpass filters are basically needed to improve the system performance and to decrease the fabrication cost. Microstrip filters gain more popularity among researchers because their day to day improvement in designs and their importance in many microwave systems including satellite communication^[1,2]. Firstly Cohn proposed Parallel coupled microstrip filters which have been widely used in the RF front end of microwave and wireless communication systems^[2]. The advantages of these filters are easy fabrication, planar structure, large fractional bandwidth and simple design process. The length of parallel coupled filter is very long and it more increases with the order of filter. For solving this problem, hairpin line filter using half wavelength folded resonator structures were developed^[3]. The benefit of this traditional hairpin topology design was compact structure, but it has the constraint of wider bandwidth and poor skirt rate due to unavoidable coupling^[1]. Small size, high selectivity and narrow bandwidth, good Return Loss (RL) and low cost are attractive features of narrowband bandpass microstrip filters. A compact microwave parallel coupled band-pass filters with smart band-width characteristics was first developed by Shamanna et al^[4]. This parallel arrangement offers comparatively great coupling for a given spacing between the resonator strips. The length of parallel coupled filter is too long and it additional will increase with the order of filter.

Many wireless applications take place at the frequency below 3 GHz^[4]. In this spectrum, achieving narrow FBW and high quality factor (Q) while maintaining small size and low cost is a difficult task. A substrate having high dielectric constant (ϵ_r) results in narrower microstrip line and narrower line gives the smaller external quality factor (Q_e) or effective input/output coupling^[1]. Narrow bandwidth and high selectivity requires high quality factor, it may be possible by using larger gaps between the coupled resonators. However, the filter size is greatly affected by increasing gap between coupled resonators^[2]. Artificial neural-network techniques are largely used in various microwave applications such as transmission-line components^[5], vias^[7], bends^[8] and coplanar waveguide (CPW) components^[9]. Neural networks have been known as useful tool for device modeling, where a mathematical model is not available or time-consuming simulation is required. The evaluation time of a neural-network model is also very fast^[6]. For these reasons, neural networks have been used for various modeling and design applications^[7,8] including passive microwave structures^[8]. Both the Neural networks and EM simulation tools are jointly used for developing microwave device models and optimization technique^{[16]-[17]}.

Conventional EM modeling method is the first option to obtain a precise model but the model assessment time of this technique is extensive, particularly when repetitive model assessments are needed. During design optimization, values of geometrical variables are required to be changed many times and each time a complete re-evaluation of the model is required^[12]. For this reason, the EM model becomes more expensive. An option to the EM model is a neural network model whose inputs are geometrical variables^[14]. The neural network model can provide solutions quickly for various values of geometrical input variables. A large number of design variables are required per structure because of increasing the complexity and different microwave geometry. For building up an accurate neural network model that can represent EM behavior of filters over a range of values of geometrical variables, we should provide EM data at sufficiently sampled points in the space of geometrical variables^[13,14]. The amount of data required increases very fast with the number of input variables. That is why, developing a neural network model which has many input variables becomes demanding as data generation becomes more exclusive. In this paper the design and analysis of microstrip hairpin bandpass filter is presented at mid-band frequency

2.2 GHz and also an artificial neural network model is suggested to determine the S-parameters of the hairpin filter for different frequencies. The efficiency of the proposed model is determined by using ANN and it is compared with the EM simulation results.

Design & Mathematical Model of Hairpin-Line Microstrip Bandpass Filters

Microstrip hairpin filter is one of the most chosen bandpass filter because of its small size and simple structure. These filters are constructed by U shape structure which is obtained by folding the resonators of parallel-coupled, half-wavelength resonator filter. On the other hand, to fold the resonators, it is essential to consider the reduction for coupled-line lengths that decreases the coupling between resonators^[1]. A constituent of hairpin bandpass resonator circuit is shown in Figure 1. The benefit of hairpin filter is the best possible space utilization as compared to coupled and parallel coupled Microstrip realizations. This space utilization is accomplished by folding of the half wavelength long resonators.

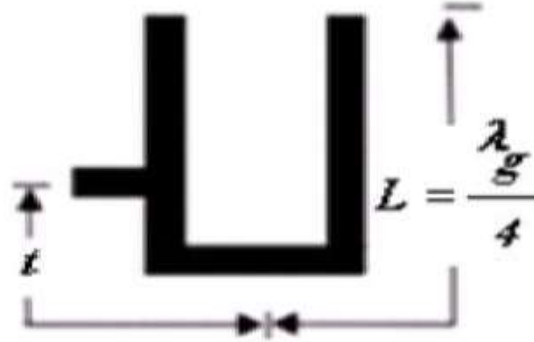


Figure 1. Element of Tapped hairpin-line Bandpass filter

Tapped line input and coupled line input are the two types of hairpin structures that are mostly used in filter realization. Usually filters employ coupled line input. The space saving is the main advantage of tapped line input as compared to coupled line input because of coupling dimensions needed for the input and output coupled line is very small. Thus tapped line input is preferred over coupled line input. If the spacing between the two arms of each resonator is too less then it acts as a pair of coupled lines, which has an effect on the coupling as well^[3].

For designing a hairpin filter, any full Wave EM simulation (IE3D, HFSS) is used. The low pass prototype (Butterworth, Chebyshev, and Bessel) is preferred for the design purpose according to the design requirement. Figure 2 represents the equivalent circuit of the n-pole hairpin bandpass filter.

Here each resonator can be modeled as a combination of inductor and capacitor. The mutual coupling coefficient between two resonators is $M_{i,i+1}$. The quality factor at the input and output are Q_{e1} and Q_{en} .

The dimensions and spacing of hair-pin filter can be determined with the help of Quality Factor and Coupling coefficient which can be derived from the designed equations as suggested below^[1]

$$Q_{e1} = \frac{g_0 g_1}{FBW} \quad (1)$$

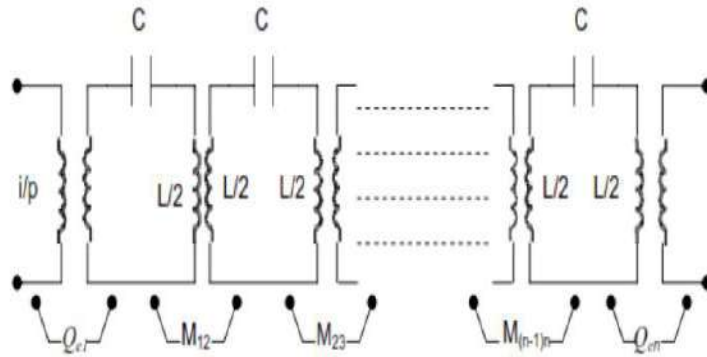


Figure 2. Equivalent Circuit of the n-pole Hairpin Bandpass Filter

$$Q_{en} = \frac{g_n g_{n+1}}{FBW} \quad (2)$$

$$M_{i,i+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \quad \text{for } i = 1 \text{ to } n - 1 \quad (3)$$

Where $g_0, g_1, g_2, \dots, g_{n+1}$ are the normalized low pass elements of the desired low pass filter approximation and FBW is the fractional bandwidth.

If hairpin filter self-coupling is neglected then the tapped position is computed as shown in Figure 1 [1].

$$t = \frac{2L}{\pi} \sin^{-1} \left(\sqrt{\frac{\pi Z_0}{2Q_e Z_r}} \right) \quad (4)$$

Where Q_e is output/input external quality factor, Z_0 is the terminating line Impedance, Z_r is the characteristic line impedance of the hairpin line, and L is the arm length of hairpin filter. If λ_g is the guided wavelength then the arm length L of hairpin filter is equal to quarter guided wavelength and can be determined by [3]

$$L = \frac{\lambda_g}{4} \quad (5)$$

The effective dielectric constant (ϵ_{re}) of a microstrip line can be calculated using the formula mentioned in [1], which is used in realization of hairpin filter. For the 3rd order conventional Hairpin-line filter, the following are the design parameters: Fractional Band width, $FBW = 20\%$ or 0.2 at mid band frequency (f_0) 2.2 GHz, di-electric constant, $\epsilon_r = 4.4$, substrate thickness, $h = 1.6$ mm, Loss tangent, $\tan \delta = 0.02$, Passband ripple 0.1 dB. A three-pole ($n = 3$) Chebyshev low pass prototype with a pass band ripple of 0.1 dB is selected. The lowpass prototype elements, suggested for a normalized lowpass cutoff frequency $\Omega_c = 1$, are $g_0 = g_4 = 1.0$, $g_1 = g_3 = 1.0316$ and $g_2 = g_4 = 1.1474$. Having obtained the lowpass parameters; the bandpass design parameters can be calculated using equations (i-iii). We use a commercial substrate (FR4/Glass-Epoxy) with a relative dielectric constant of 4.4 and a thickness

of 1.6 mm for microstrip realization. The hairpin resonators used to have a line width of 2 mm which results in $Z_r = 59$ ohm on the substrate and a separation of 4 mm between the two arms. The quarter guided wavelength length L of hairpin resonator is 23.27 mm at midband frequency $f_0=2.2$ GHz. The Coupling coefficient and Quality Factor can be calculated from (i) and (iii) which gives $M_{1,2} = M_{2,3} = 0.184$ and $Q_{e1} = 5.158$. Hence the spacing between the resonators is 0.4 mm which is calculated with the help of coupling coefficient. The filter is designed to have tapped line input and output. The tapped line is selected in such a way that the characteristic impedance matches to a terminating impedance $Z_0 = 50$ ohms. Hence, the tapped line is 3 mm wide on the substrate. The tapping location (t) is calculated using equation (iv) which is 7.89 mm. as shown in Figure 3.

Layout of Microstrip Hairpin-Line Bandpass Filters

The layout of the final filter design with all the determined dimensions is illustrated in Figure 3 which is obtained by Zeland IE3D full wave EM simulation software. The length of first U shaped resonator is $L_1=18.27$ mm and the length of second U shaped resonator is $L_2= 19.27$ mm with separation between first and second resonator is of 0.4mm and the separation between second and third resonator is also 0.4 mm. The filter is designed to have a tapped line at the input and output. The final geometry of the filter is shown in figure3. The 3-dimensional geometry of the proposed design is shown in figure 4 and the frequency response of the filter is shown in figure 6.

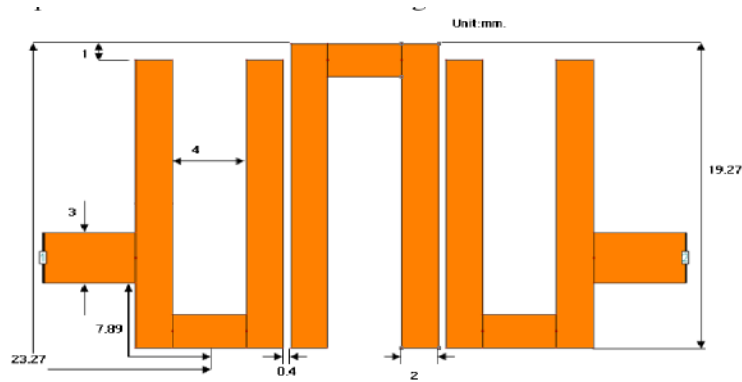


Figure 3. Layout of a Microstrip hairpin- line bandpass filter on FR4 substrate

Photograph of the fabricated prototype of Microstrip hairpin-line filter on an FR4 substrate is shown in figure 5. Cross sectional area of the fabricated Microstrip hairpin line filter is $(35 \times 19.27) \text{ mm}^2$. Hence the design becomes more compact as compared to previous one^[17].

Implementation and Results

The full-wave EM simulated performance of the designed hairpin line filter is illustrated in Figure 6, which represents the magnitude response of microstrip hairpin line bandpass filter.

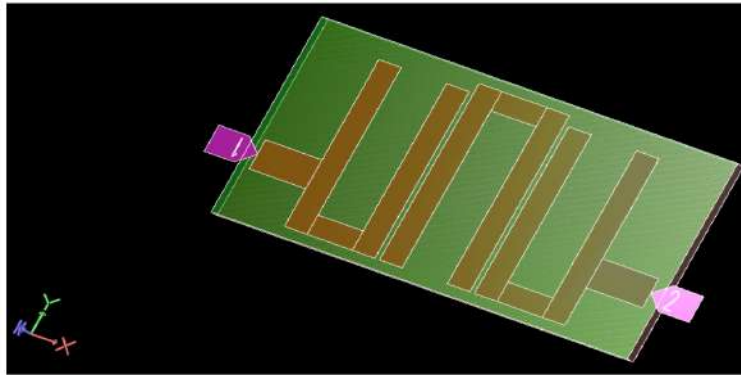


Figure 4. 3-D Geometry of a Microstrip hairpin-line bandpass filter

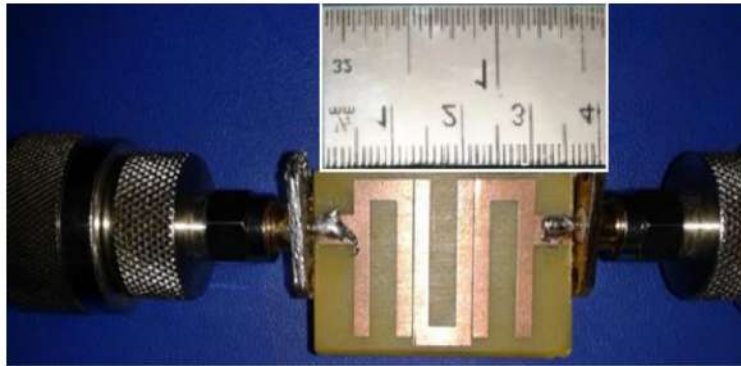


Figure 5. Fabricated microstrip hairpin-line band pass filter

Return- loss and insertion-loss expressed in terms of S-parameters (S_{11} , S_{21}). Magnitude of S - parameters is summarized in table 1 which is represented in dB form.

Figure 7 represents the phase response of microstrip hairpin line bandpass filter which represents the group delay, phase or angle variations of S-Parameters in degrees.

Practically the results are measured with the help of FS-315 Spectrum analyzer. Figure 8 represents the comparison of measured and simulated insertion loss of filter

For collecting more samples for ANN training, the length of second U shaped resonator ($L_2=19.27$ mm) is changed then different magnitudes and phases of S-parameters are obtained at mid-band frequency 2.2 GHz. If the length of second U shaped resonator is changed and keeping all other parameters constants. Then the resultant graph is obtained between insertion loss (S_{21}) or return loss (S_{11}) and frequency as shown in Figure 9, 10 and 11 which represent the simulated performance of filter when the length of second U shaped resonator becomes 20.27, 21.27 and 22.27 respectively. Similarly more results are obtained for different dimensions of second U shaped resonator.

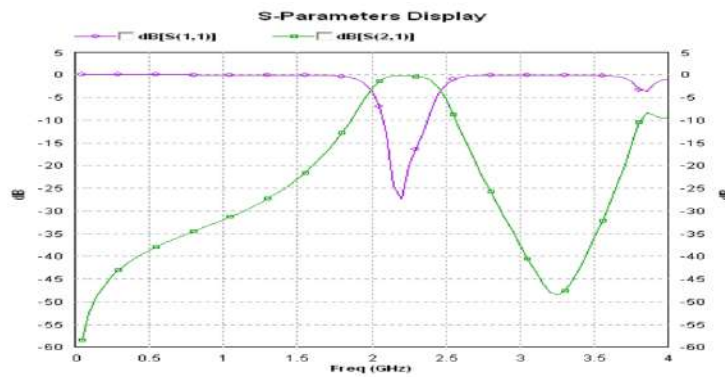


Figure 6. full-wave EM simulated performance of the microstrip hairpin-line bandpass filter

Table 1. S-Parameters (Magnitude in dB)

Frequency(GHz)	S_{11} (dB)	S_{21} (dB)
1.6	-0.1104	-20.14
1.8	-0.3572	-12.74
2	-3.549	-3.073
2.2	-27.4	-0.2954
2.4	-7.954	-1.254
2.6	-0.5285	-12.44
2.8	-0.1377	-25.75
3.4	-0.1127	-42.42
3.6	-0.2856	-28.35

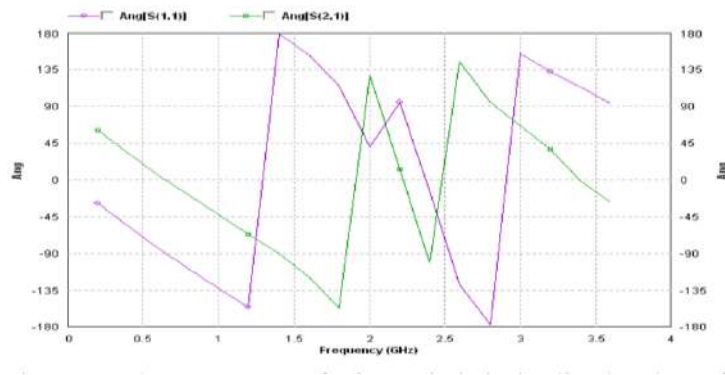


Figure 7. Phase response of microstrip hairpin -line bandpass filter

When the length of second U shaped resonator (L_2) is 21.27 mm. Then following results are obtained as given in figure 10.

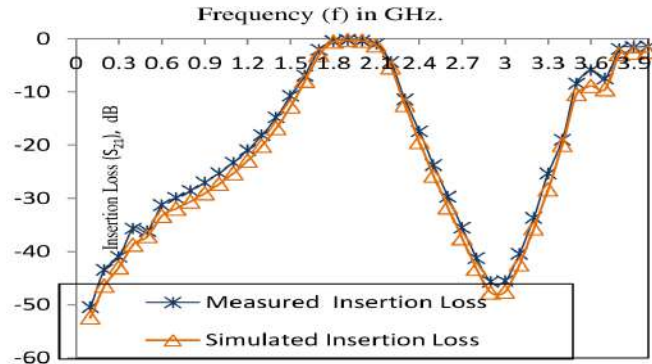


Figure 8: Comparison of measured and simulated performance

Figure 8. Comparison of measured and simulated performance (S_{21}) of the microstrip hairpin-line bandpass filter

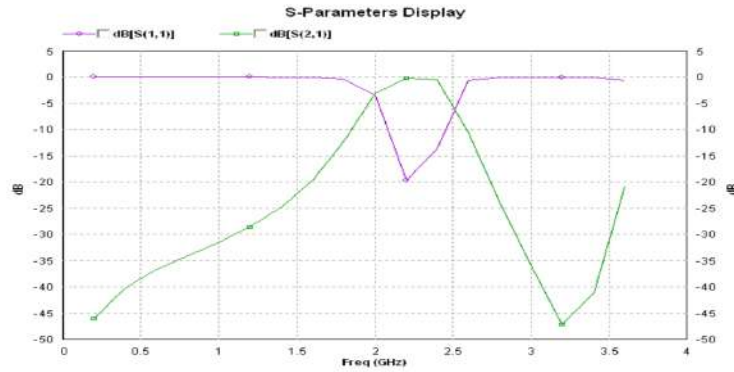


Figure 9. Magnitude response of microstrip hairpin-line bandpass filter when $L_2 = 20.27$ mm

In microstrip hairpin-line bandpass filter, changing the dimensions of second U shaped resonator (L_2) and keeping all other parameters remain same. Then for centre frequency $f_0 = 2.2$ GHz, following IE3D simulated results are received in terms of Scattering-Parameters and are summarized in table 2.

ANN Models For The Analysis Of Microstrip Hairpin Line Band-Pass Filter

The ANN model used in this paper is illustrated in Figure 12 which consists of three layers (input layer, hidden layer, output layer). It is based on the back propagation learning algorithms^[13]. The hidden layer consists of nonlinear activation functions, and permits modeling of complex input/output relationships between multiple inputs and output neurons^[17]. Inputs and output layers of neurons are interconnected by different sets of weights. Training of the neural model can be achieved by adjusting these weights to give the desired response. ANN responses are compared to the known outputs and then the respective errors are calculated easily.

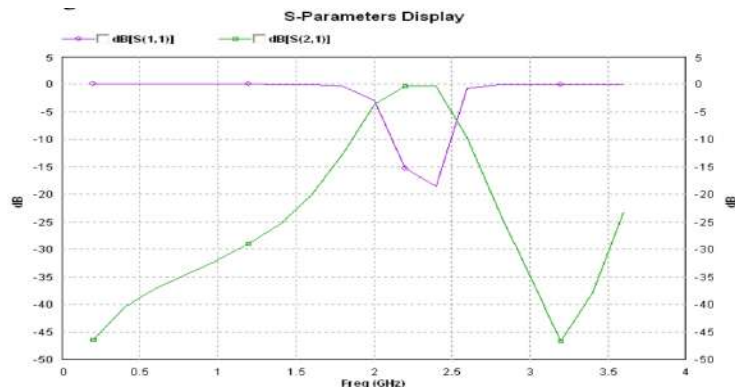


Figure 10. Magnitude response of microstrip hairpin line bandpass filter when $L_2 = 21.25$ mm

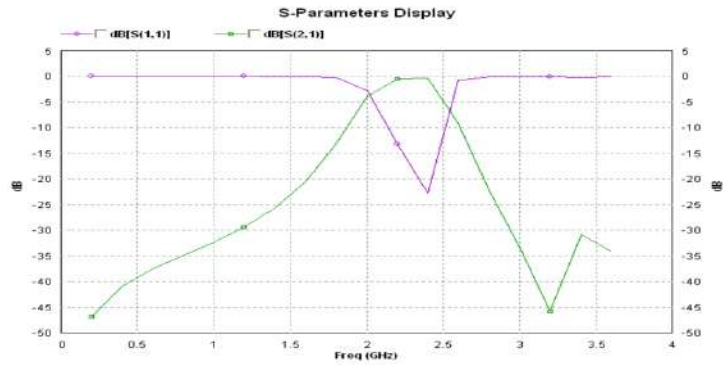


Figure 11. Magnitude response of microstrip hairpin-line bandpass filter when $L_2 = 22.27$ mm

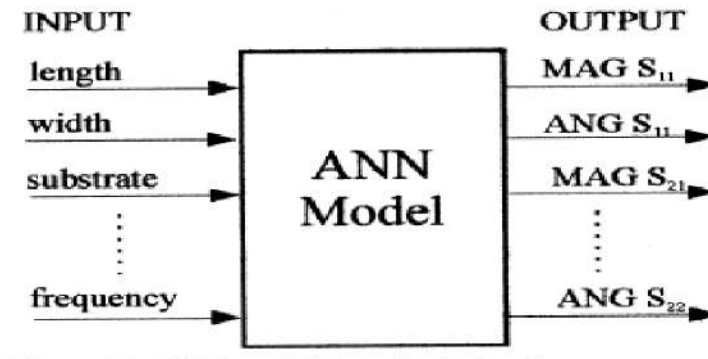
Training process is running until the errors become less as much as possible than the given prescribed values^[16]. For developing a neural model for this filter, many numbers of EM simulations need to be performed first. The length, width of second U shaped resonator and frequency are taken as the input parameters whereas the scattering parameters are taken at the output parameters or targets, which are given in form of dB. The variation ranges of input parameters are listed in Table 2. The training data has been obtained in the EM simulation for a cut-off frequency of 2.2 GHz. S-Parameters received after the neural network training are illustrated in table 3.

Results and Discussion

Table 2 and 3 shows the comparison between the data obtained from the EM simulation and data received after the ANN training for the filter. In ANN training, we pass the full set of input samples through the neural network to compute the least squared error function used in the back propagation of the errors step. Each such pass is called an *epoch*. Training graph received after ANN training for Magnitudes

Table 2. IE3D Simulated Results

INPUTS (length of first and second U-shaped resonators) in mm.		TARGETS/OUTPUTS (Scattering-Parameters) in dB.	
Length of first U-shaped resonators (mm.)	Length of second U-shaped resonators (mm)	S_{11} (dB)	S_{21} (dB)
18.27	19.27	-27.4	-0.2954
18.27	20.27	-19.73	-0.3333
18.27	21.27	-15.38	-0.4247
18.27	22.27	-13.23	-0.5186
18.27	23.27	-11.26	-0.6289
18.27	24.27	-10.39	-0.7396

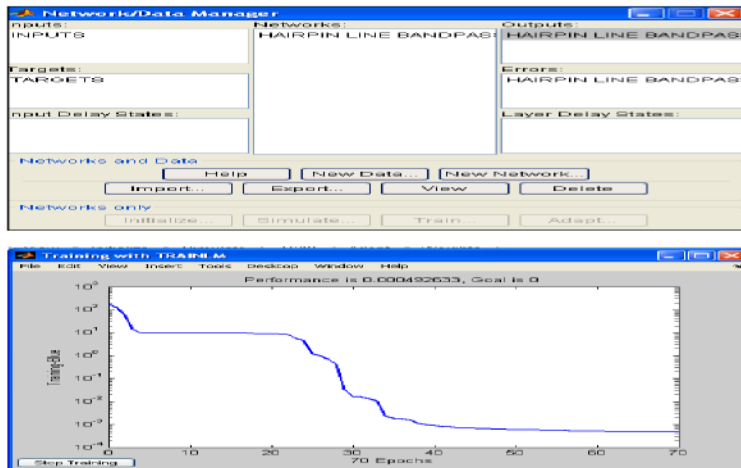
**Figure 12.** ANN model for calculating S-parameters of Microstrip hairpin-line bandpass filter

of S-Parameters is shown in figure 13. It represents that training performs in 70 epochs and error get reduced from 10^2 to 10^{-3} after ANN Training performed in *MATLAB* and the more accurate results (S-parameters) are obtained.

Figure 14 represents the ANN architecture for Microstrip hairpin-line bandpass filter.

Table 3. Ann Trained Results

INPUTS (length of first and second U-shaped resonators in mm.)		TARGETS/OUTPUTS (Scattering-Parameters) in dB.	
Length of first U-shaped resonator (mm.)	Length of second U-shaped resonator (mm.)	S_{11} (dB)	S_{21} (dB)
18.27	19.27	-27.3996	-0.2899
18.27	20.27	-19.729	-0.3299
18.27	21.27	-15.369	-0.4189
18.27	22.27	-13.228	-0.5098
18.27	23.27	-11.259	-0.6198
18.27	24.27	-10.378	-0.7288

**Figure 13.** ANN Training Graph Results for Microstrip hairpin-line bandpass filter

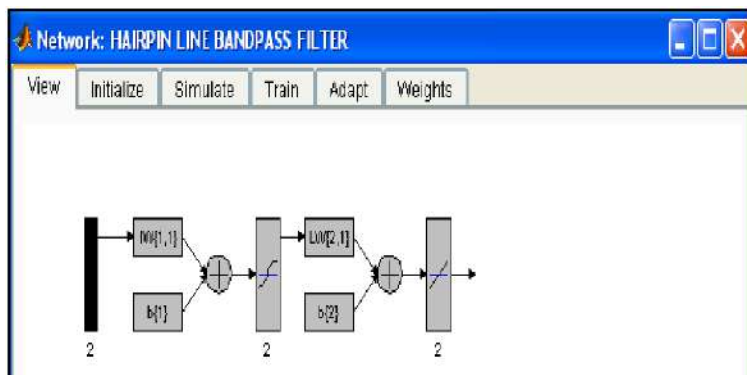


Figure 14. ANN architecture for Microstrip hairpin-line bandpass filter

It is clear from the above neural network architecture, it consists of three layers. The three-layer network has one input layer (layer 1), one hidden layer (layer 2) and one output layer (layer 3). Input and output layer consists of two neurons. An output layer is a layer that produces the network outputs. Length of first and second U-shaped resonators and mid-band frequency are given at the input neurons while the S-Parameters (S_{11} & S_{21}) are obtained from the output neurons in dB form. A constant input 1 is given to the biases for each neuron. The outputs of each intermediate layer are the inputs to the next layer.

Conclusion

An effective artificial neural networks modeling technique is proposed for the design and analysis of a Microstrip hairpin-line bandpass filter at the mid-band frequency 2.2 GHz with low insertion loss and high return loss. It is applicable for narrowband applications or S-band applications such as radar and satellite communication. The passband of the filter ranges from 2 to 2.4 GHz. It has observed that the developed Artificial Neural Network model for the considered microstrip band-pass filter can be as reliable and accurate as an EM simulator and also it is computationally more prevailing. More compact filter structure is obtained with improved performance and quicker convergence by using different learning algorithms. The artificial neural networks are proposed because they offer a fast and quite accurate design before fabrication of hairpin-line filter. The reduction in CPU time is also a great advantage of applying ANN model for the filter design. IE3D Simulator took about 10-15 minutes on a computer (2.29 GHZ CPU and 2 GB RAM) to perform the design optimization of the filter, but the ANN model took only 5-6 seconds (in MATLAB) to perform the same task on the same computer. More precise and straightforward neural models are proposed to calculate the Scattering parameters of Microstrip hairpin-line band-pass filter for the desired application.

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