(IJCSNT) International Journal of Communication Systems and Network Technologies
ISSN Number: 2053-6283
Volume 2, Issue No. 1, 11–23
©The Author(s) 2013
https://journals.mirlabs.in/index.php/ijcsnt
DOI- 10.18486/ijcsnt/2.1.17
IJCSNT

Artificial Neural Network Design of Stub Microstrip Band-pass Filters

Vivek Singh Kushwah[1], Geetam S Tomar[2], Sarita S Bhadauria[3]

Abstract

In this paper an Artificial neural network (ANN) design technique for a Stub Microstrip Band-pass filter is presented. Essential dimensions of the microstrip filter layout are used to get the relationship in the input-outputs of ANN model. This paper presents the design and analysis of Stub Microstrip Band-pass Filter at mid-band frequency 1.8 GHz which gives improved bandwidth and minimum insertion loss of -0.5899 dB and return loss of -36.67 dB. Also artificial neural network architecture is proposed to determine the Magnitude variation of scattering parameters (S-parameters) of these Microstrip Band-pass filters for various dimensions. When the ANN model is produced, it has been exposed to be as exact and veracious as an EM simulator and it is computationally more effective in the design. The simulation is performed using the commercial software IE3D 14.1 and ANN Training of S-Parameters are performed in MATLAB 7.1 Software.

Keywords

Stub Microstrip Band Pass Filters, ANN Model, MATLAB, IE3D EM Simulation, S-parameters, Training Algorithm.

Received: 05 january 2012; **Revised:** 31 March 2013; **Accepted:** 20 April 2013;
Published: 30 April 2013;

[1]Amity University, Gwalior, Madhya Pradesh, India.
[2]Machine Intelligence Research Labs, Gwalior, Madhya Pradesh, India.
[3]Madhav Institute of Technology and Science, Gwalior, Madhya Pradesh, India.

Corresponding author:
Email: vivek_kushwah@rediffmail.com

Introduction

A filter that passes only one band of frequencies and rejects both higher and lower frequencies is known as Band-pass filter. The Bandwidth of the pass band of a band pass filter is defined as the frequency difference between lower and upper corner frequencies, such as -3 dB points[1,15]. In standard Bandpass filters the mid-band frequency is either geometrically or arithmetically calculated.

$$\text{Geometrically:} \quad f_0 = \sqrt{(f_1 \times f_2)} \tag{1}$$

$$\text{Arithmetically:} \quad f_0 = \frac{1}{2}(f_1 \times f_2) \tag{2}$$

Where f_1 and f_2 are lower and upper corner frequencies. A Microstrip Band-pass filter has many important properties such as easy fabrication, large bandwidth, compact size, and very low insertion loss. Therefore, it has many applications in mobile communication and microwave applications[1]. Neural-network techniques are widely used in many microwave applications such as embedded passives[3], transmission-line components[4–6], bends[8], vias[7], coplanar waveguide (CPW) components[9], spiral inductors[10], FETs[11,12] amplifiers etc. Many RF/microwave engineers and researchers are working in this field and also taking serious interest in this technology. ANN has many applications in various fields like speech processing, biomedical engineering, pattern recognition, control etc. ANNs can also be used in RF and microwave Computer-Aided Design (CAD) problems[13,14,16]. This paper presents the design and analysis of Microstrip Band-pass filters at mid-band frequency 1.8 GHz with good wide-band and very low insertion loss and an artificial neural network model is proposed to determine the Magnitude variation of scattering parameters (S-parameters) in Microstrip Band-pass filters for various dimensions.

Design of Stub Microstrip Bandpass Filters

Stub Microstrip Band-pass filters can be designed as shown in Figure 1, which is made of shunt short-circuited stubs that are $\lambda_{g0}/4$ long with connecting lines that are also $\lambda_{g0}/4$ long, where λ_{g0} is the guided wavelength in the medium of propagation at the center frequency f_0. For a filter of degree n as given below, the stub band-pass filter characteristics depends on the characteristic admittances of the stub lines denoted by Y_i ($i = 1$ to n) and the characteristic admittances of the connecting lines denoted by $Y_{i,i+1}$ ($i = 1$ to $n-1$).

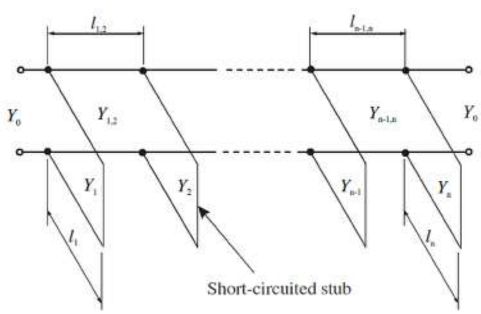

Figure 1. Transmission line band-pass filter with quarter-wavelength short-circuited stubs.

The design equations for determining these characteristic admittances described in[1] are given by

$$\theta = \frac{\pi}{2}\left(1 - \frac{FBW}{2}\right), \quad h = 2 \tag{3}$$

$$\frac{J_{1,2}}{Y_0} = g_0\sqrt{\frac{hg_1}{g_2}}, \qquad \frac{J_{n-1,n}}{Y_0} = g_0\sqrt{\frac{hg_1 g_{n+1}}{g_0 g_{n-1}}} \tag{4}$$

$$\frac{J_{i,i+1}}{Y_0} = \sqrt{\frac{hg_0 g_1}{g_i g_{i+1}}} \quad \text{for } i = 2 \text{ to } n-2 \tag{5}$$

$$N_{i,i+1} = \sqrt{\left(\frac{J_{i,i+1}}{Y_0}\right)^2 + \left(\frac{hg_0 g_1 \tan\theta}{2}\right)^2} \tag{6}$$

$$Y_1 = g_0 g_1 Y_0 \left(1 - \frac{h}{2}\right)\tan\theta + Y_0\left(N_{1,2} - \frac{J_{1,2}}{Y_0}\right) \tag{7}$$

$$Y_{i,i+1} = Y_0\left(\frac{J_{i,i+1}}{Y_0}\right) \tag{8}$$

Where $h = 2$, dimensionless constant, g_0, g_1 and g_n are the element values of a ladder-type lowpass prototype filter such as a Chebyshev, given for a normalized cutoff $\Omega_c = 1.0$.

$J_{i,i+1}$ = Characteristic admittances of J-inverters. Y_0 = Characteristic admittances of microstrip line.

To express how to design this type of microstrip filter, let us start with a five pole ($n = 5$) Chebyshev low-pass prototype with a 0.1 dB passband ripple. The prototype parameters are

$$\begin{aligned} g_0 &= g_6 = 1.0, \quad g_1 = g_5 = 1.1468 \\ g_2 &= g_4 = 1.3712, \quad g_3 = 1.9750 \end{aligned} \tag{9}$$

The bandpass filter is designed to have a fractional bandwidth $FBW = 0.5$ at a mid-band frequency $f_0 = 1.8$ GHz. A 50 ohm terminal line impedance is chosen, which gives $Y_0 = 1/50$ mhos. The computed design parameters using equation (1)–(8) are summarized in Table 1.

Table 1. Circuit design parameters of a five-pole, stub band-pass filter with $\lambda_{g0}/4$ short-circuited stubs

i	Y_i (mhos)	$Y_{i,i+1}$ (mhos)
1	0.03525	0.02587
2	0.06937	0.02787
3	0.06824	0.02787
4	0.06937	0.02587
5	0.03525	

For the microstrip filter design, we use a dielectric substrate with a relative dielectric constant of 10.2 and a thickness of 0.635 mm. Using the microstrip design equations, the widths and guided quarter-wavelengths associated with the characteristic admittances in Table 1 can be found and are listed in Table 2[2].

Table 2. Microstrip design parameters of a five-pole, stub band-pass filter with $\lambda_{g0}/4$ short-circuited stubs

i	W_i (mm)	$\lambda_{g0,i}/4$	$W_{i,i+1}$	$\lambda_{g0,i+1}/4$
1	1.61	15.2	0.97	15.61
2	4.00	14.47	1.10	15.51
3	3.93	14.48	1.10	15.51
4	4.00	14.47	0.97	15.61
5	1.61	15.2		

Figure 2(a) shows the layout of the designed stub microstrip filter and Figure 2(b) plots the filter frequency responses obtained by full-wave EM simulations. In general, the performance is seen to be in good agreement with the design consideration. It is also seen that the filter has a second pass-band centered by $3f_0$, but exhibits an attenuation pole at $2f_0$, which are typical stop-band characteristics of this type of filter. Filters of this type are primarily used as wide-band filters, because if narrow-band filters are designed in this manner, their stubs will have undoubtly low impedance levels[15].

Mathematical Model

A Stub microstrip band-pass filter with five short-circuited stubs ($n = 5$) and a fractional bandwidth $FBW = 0.5$ at a mid-band frequency $f_0 = 1.8$ GHz is designed. Commercial substrate Duroid (RT/D 6010LM) with a relative dielectric constant of 10.2 and a thickness of 0.635 mm. is used. $\varepsilon_r = 10.2$, $h = 0.635$ mm.

$$\text{Fractional bandwidth (FBW)} = \frac{f_2 - f_1}{f_0} \tag{10}$$

$$\text{Mid-band frequency } (f_0) = \sqrt{f_1 f_2} \tag{11}$$

From equation (i) & (ii): $f_1 = 1.35$ GHz & $f_2 = 2.25$ GHz.

From equation (1): $\theta = \frac{\pi}{2}\left(1 - \frac{0.5}{2}\right) = 67.5°$.

From equation (2): $\frac{J_{1,2}}{Y_0} = g_0\sqrt{\frac{hg_1}{g_2}} = \sqrt{\frac{2\times1.1468}{1.3712}}$. Here $Y_0 = 1/50$ mhos.

Now from equation (4):

$$N_{1,2} = \sqrt{\left(\frac{0.02587}{(1/50)}\right)^2 + \left(\frac{2\times1\times1.1468\ \tan 67.5°}{2}\right)^2} = 3.0558 \tag{12}$$

From equation (iii), (v), (vii) & (5):

$$Y_1 = 1 \times \frac{1}{50}\left(1 - \frac{2}{2}\right)1.1468 \times \tan 67.5° + \frac{1}{50}\left(3.0558 - \frac{0.02587}{(1/50)}\right) \tag{13}$$

$Y_1 = 0.03525$. Hence $Z_1 = \frac{1}{Y_1} = \frac{1}{0.03525} = 28.36\ \Omega$.

From equation (8): $Y_{1,2} = Y_0 \left(\frac{J_{1,2}}{Y_0}\right) = 0.02587$, $Z_{1,2} = \frac{1}{Y_{1,2}} = 38.65\ \Omega$. Hence:

$$\begin{aligned} &Y_{1,2} = Y_{4,5} = 0.02587, \quad Z_{1,2} = Z_{4,5} = 38.65\ \Omega \\ &Y_1 = Y_5 = 0.03525, \quad Z_1 = Z_5 = 28.36\ \Omega \\ &Y_2 = Y_4 = 0.06937, \quad Z_2 = Z_4 = 14.41\ \Omega \\ &Y_{2,3} = Y_{3,4} = 0.02787, \quad Z_{2,3} = Z_{3,4} = 35.88\ \Omega \\ &Y_3 = 0.06824, \quad Z_3 = 14.65\ \Omega \end{aligned}$$

Now calculate the microstrip line width and quarter guided wavelength for different line impedance. For $Z_1 = Z_5 = 28.36\ \Omega$, if $\frac{W}{h} \geq 2$, then

$$\frac{W_1}{h} = \frac{2}{\pi}\left[(B-1) - \ln(2B-1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left\{\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right\}\right] \tag{14}$$

Where

$$B = \frac{60\pi^2}{Z_1\sqrt{\varepsilon_r}} = \frac{591.57}{28.36\sqrt{10.2}} = 6.53 \tag{15}$$

From equation (ix) & (x), substitute the value of B in equation (x), then following results are obtained: $W_1 = W_5 = 1.61$ mm.

$$\text{Guided wavelength } (\lambda_g) = \frac{300}{f(\text{GHz})\sqrt{\varepsilon_{\text{reff}}}} \tag{16}$$

$$\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-1/2} \tag{17}$$

Where $\varepsilon_{\text{reff}}$ is the effective dielectric constant. From equation (xii), $\varepsilon_{\text{reff}} = 7.51$. From equation (xi), $\lambda g_1 = \frac{300}{1.8\sqrt{7.51}} = 60.8$. Length of short circuit stub is equal to quarter guided wavelength, i.e. length of stub $= \frac{\lambda g_1}{4} = \frac{\lambda g_5}{4} = \frac{60.8}{4} = 15.2$ mm. Similarly calculate the microstrip line width and quarter guided wavelength for other line impedances.

IE3D Layout of Stub Microstrip Band Pass Filter

The final 2-D layout of Stub microstrip band-pass filter design is shown in Figure 2(a) with the help of IE3D EM simulator[17].

3-D geometry of the designed Stub microstrip band-pass filter with the five short-circuited stubs is shown in below figure 2(b).

Cross sectional area of the designed stub microstrip band-pass filter is $(72.24 \times 16.17)\ \text{mm}^2$.

Implementation and Results

The full-wave EM simulated performance of the designed stub microstrip band-pass filter is illustrated in Figure 3(a).

Return-loss and insertion-loss expressed in terms of S-parameters (S_{11}, S_{21}). Magnitude of S-parameters is summarized in table 3 which is represented in dB form.

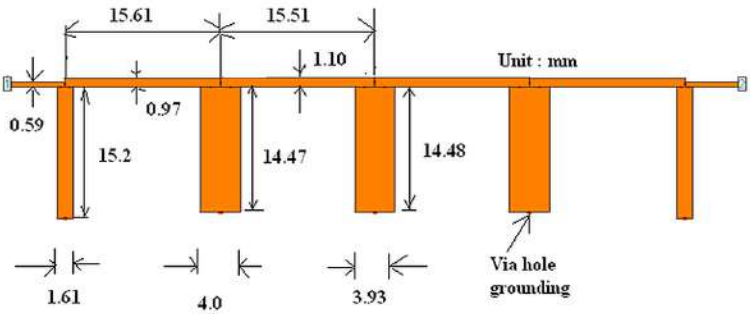

Figure 2. Layout of a Stub microstrip band-pass filter with the five quarter wavelength short-circuited stubs on a substrate with a relative dielectric constant of 10.2 and thickness 0.635 mm

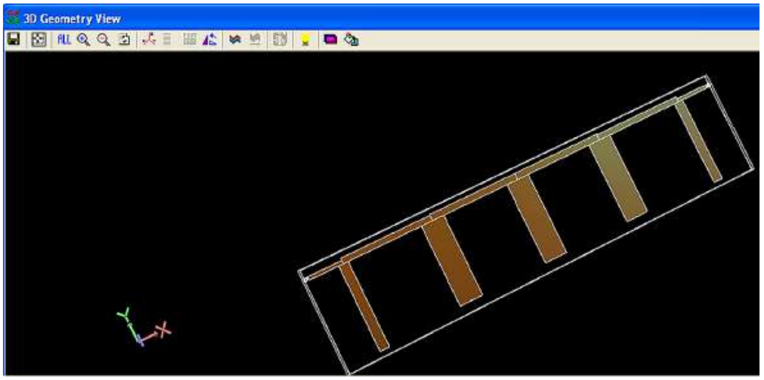

Figure 3. 3-D Geometry of a stub microstrip band-pass filter

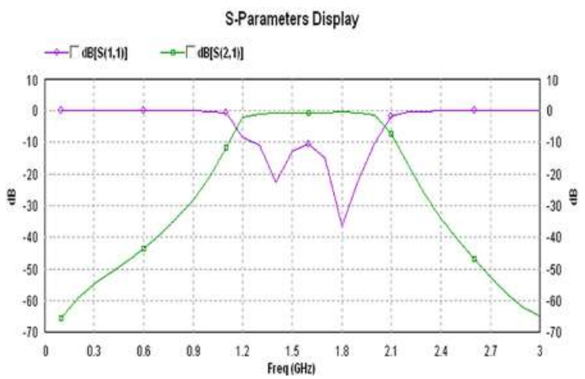

Figure 4. full-wave EM simulated performance of the stub microstrip bandpass filter

Table 3. S-Parameters (Magnitude in dB, Phase in Degrees)

Freq[GHz]	dB[S(1,1)]	Ang[S(1,1)]	dB[S(2,1)]	Ang[S(2,1)]
0.1	-3.15e-002	172.8	-65.38	78.01
0.2	-3.753e-002	165.5	-59.22	71.82
0.3	-4.363e-002	158	-54.94	64.39
0.4	-5.031e-002	150.3	-51.16	56.43
0.5	-5.813e-002	142.2	-47.42	48
0.6	-6.807e-002	133.5	-43.44	38.95
0.7	-8.2e-002	123.8	-39.07	28.99
0.8	-0.1043	112.8	-34.08	17.55
0.9	-0.1475	99.4	-28.21	3.56
1	-0.2646	81.51	-21.03	-15.54
1.1	-0.865	52.32	-11.79	-48.07
1.2	-8.457	-1.284	-2.329	-124
1.3	-10.95	46.4	-1.101	151.6
1.4	-22.88	-17.62	-0.6415	90.61
1.5	-12.8	123.7	-0.8036	33.37
1.6	-10.52	70.98	-0.9487	-17.89
1.7	-15.17	16.24	-0.6831	-70.21
1.8	-36.67	-90.27	-0.5899	-126.6
1.9	-22.04	76.86	-0.7298	171.9
2	-10.18	-7.369	-1.52	96.85
2.1	-1.916	-91.45	-7.356	8.19
2.2	-0.5112	-144.3	-17.33	-47.83
2.3	-0.2771	-174.1	-26.29	-79.49
2.4	-0.1974	165.9	-33.96	-101.1
2.5	-0.157	150.6	-40.71	-118.1
2.6	-0.1325	138	-46.8	-133.1
2.7	-0.1165	127.2	-52.49	-147.6
2.8	-0.1056	117.4	-57.68	-163.3
2.9	-9.852e-002	108.4	-62.1	178.4
3	-9.442e-002	99.8	-64.83	159.1

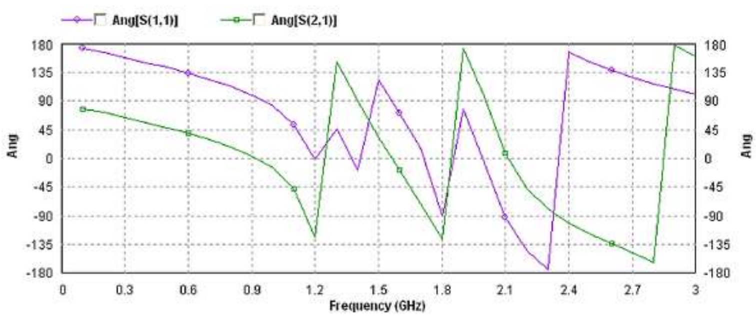

Figure 5. Phase response of stub microstrip bandpass filter

Figure 3(b) represents the phase response of stub microstrip band-pass filter which represents the phase variation of S-parameters in degrees.

Now changing the dimensions of short circuited Stubs, quarter guided wavelength and microstrip line width; different S-parameters are obtained for different dimensions. If only the line width W_3 is changed and keeping all other microstrip line width & quarter guided wavelength remain same. If $W_3 = 4.43$ mm. and $\frac{\lambda g3}{4} = 14.48$ mm. Then the resultant response is obtained between insertion loss (S_{21}) and frequency as shown in figure 4.

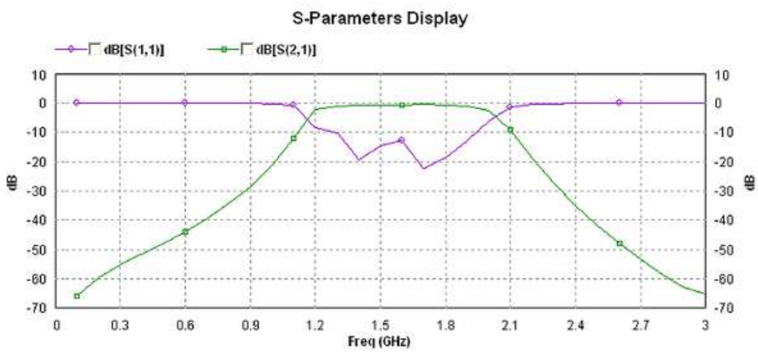

Figure 6. Magnitude response of Band-pass filters when width W_3 is 4.43 mm

If line width $W_3 = 4.93$. Then following results are obtained as given in figure 5.

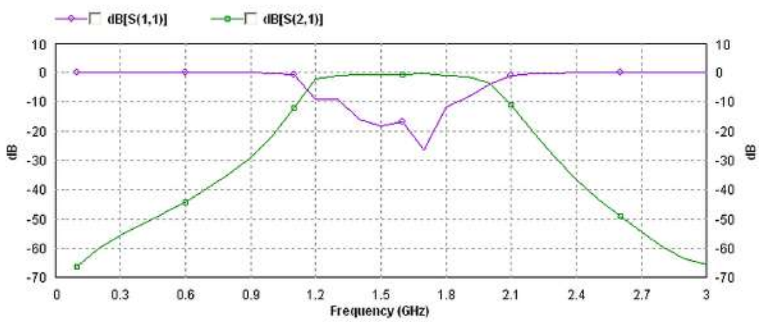

Figure 7. Magnitude response of Band-pass filter when width W_3 is 4.93 mm

In Band-pass filter, varying only the line width W_3 of short circuited stubs and keeping quarter guided wavelength, line width W_1 and W_3 constant. Then For mid-band frequency $f_o = 1.8$ GHz, following IE3D simulated results are obtained in terms of S-Parameters and are given in table 4.

Table 4. IE3D Simulated Results

INPUTS (Width & length of Stubs) in mm.		TARGETS/OUTPUTS (S-Parameters) in dB.	
Length $\frac{\lambda g3}{4}$ (mm.)	Width W_3 (mm.)	S_{11} (dB)	S_{21} (dB)
14.48	3.93	-36.67	-0.5899
14.48	4.43	-18.73	-0.6764
14.48	4.93	-11.89	-0.9681
14.48	5.43	-8.79	-1.352
14.48	5.93	-6.428	-1.973
14.48	6.93	-3.741	-3.591

ANN Architecture for the Analysis of Stub Microstrip Band-pass Filter

The ANN architecture used in this paper is shown in Figure 6 which consists of an input layer, an output layer and one hidden layer. It is utilizing the back propagation training algorithms[4]. The hidden layer consists of nonlinear activation functions, and gives modeling of complex input/output relationships between multiple inputs and multiple outputs[13]. Inputs and outputs are linked by many sets of weights. Training of the ANN model can be performed by adjusting these weights to give the accurate response. ANN trained outputs is compared to the known outputs and then the respective errors are calculated. Training process keeps on working until the errors get reduced as much as possible than the given prescribed values[14]. In order to make an ANN model for this band-pass filter, a lot of EM simulations need to be performed first.

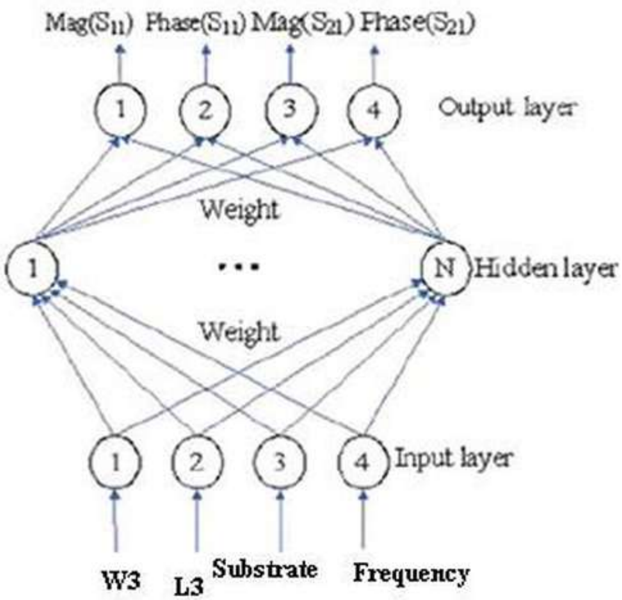

Figure 8. Neural model for calculating Magnitude & Phase of S-parameters of Microstrip Band-pass Filter

The width of microstrip line, quarter guided wavelength, substrate Dielectric constant and frequency are taken as the input parameters whereas scattering parameters are taken as the output parameters or targets, which are represented in terms of dB. The variation ranges of input parameters are listed in Table 4. The training data has been obtained in the EM simulation over a mid-band frequency of 1.8 GHz. S-Parameters obtained after the ANN training are given in table 5.

Table 5. ANN Trained Results

INPUTS (Width & length of Stubs) in mm.		TARGETS/OUTPUTS (S-Parameters) in dB.	
Length $\frac{\lambda g3}{4}$ (mm.)	Width W_3 (mm.)	S_{11} (dB)	S_{21} (dB)
14.48	3.93	-36.5319	-0.39801
14.48	4.43	-19.1396	-1.0182
14.48	4.93	-11.5355	-1.2894
14.48	5.43	-8.3001	-1.4047
14.48	5.93	-6.9396	-1.4533
14.48	6.93	-3.7416	-3.5865

Results and Discussion

Training graph obtained after ANN training of samples for Magnitudes of S-Parameters is shown in figure 7. Here the full set of input samples is passed through the Artificial 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*. Figure 7 shows that training perform in 100 epochs and error get reduced from 10^2 to 10^{-1}.

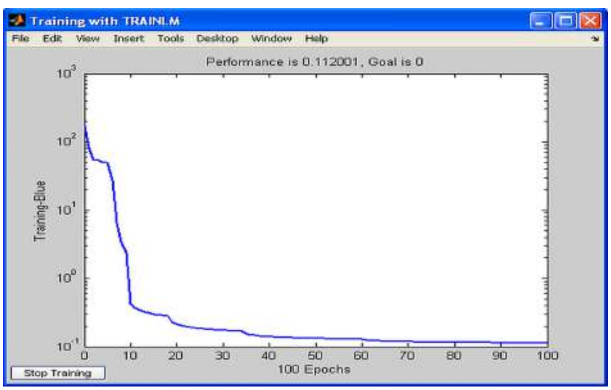

Figure 9. ANN Training Graph Results for Band-pass filter

It represents that error is reduced as much as possible, so that the accurate and error free results are obtained after the ANN training. Table 4 and 5 give the comparison between the data obtained from the EM simulation and ANN trained data for the filter. Figure 8 represents the ANN architecture for Microstrip Band-Pass filters.

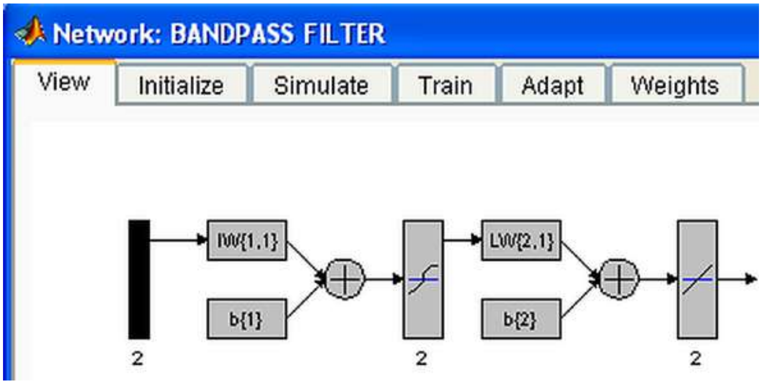

Figure 10. ANN architecture for Microstrip Band-Pass filters

As shown in the above neural network architecture, it consists of three layers. The three-layer neural network has one input layer (layer 1), one hidden layer (layer 2) and one output layer (layer 3). An output layer is a layer that produces the network output. Input and output layer consists of two neurons. Mid-band frequency (f_o), quarter guided wavelength (L_3) and width (W_3) are applied 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 applied to the biases for each neuron. The outputs of each intermediate layer are the inputs to the next layer.

Conclusion

This paper presents the structure and application of artificial neural networks in the design of a Stub Microstrip Band-pass filter at the mid-band frequency 1.8 GHz with low insertion loss (-0.39801 dB). It has noted that the developed Artificial Neural Network model for the considered Microstrip Band-pass filter can be as authentic and accurate as an EM simulator and also it is computationally more effective. Accurate and simple neural models are described to calculate the S-parameters of Microstrip Band-Pass filter for the required design consideration and trained by using different training algorithms to obtain low insertion loss better performance and fast speed with a compact structure.

References

[1] Jia-Shen G. Hong & M.J. Lancaster, "Microstrip Filters for RF/Microwave Applications" (1/e), John Wiley & Sons Inc., 2001.

[2] D.M. Pozar, "Microwave Engineering" (2/e), John Wiley, 2000.

[3] V. K. Devabhaktuni, M. Yagoub, and Q. J. Zhang, "A robust algorithm for automatic development of neural network models for microwave applications," IEEE Trans. Microwave Theory Tech., vol. 49, pp. 2282-2291, Dec. 2001.

[4] V. K. Devabhaktuni, C. Xi, F. Wang, and Q. J. Zhang, "Robust training of microwave neural models," Int. J. RF Microwave Computer-Aided Eng., vol. 12, pp. 109-124, 2002.

[5] J. Lakshmi Narayana, Dr. K. Sri Rama Krishna and Dr. L. Pratap Reddy, "Design of Microstrip Antennas using Artificial Neural Networks", International Conference on Computational Intelligence and Multimedia Applications, SivaKasi, pp. 332-334, 2007.

[6] J. Lakshmi Narayana, Dr. K. Sri Rama Krishna and Dr. L. Pratap Reddy, "ANN Modles for coplanar strip line analysis and synthesis", International Journal of Computer Science and Network security, Korea, Vol. 08, No. 10, pp. 200-204. Oct 2008.

[7] P. M. Watson and K. C. Gupta, "EM-ANN models for microstrip vias and interconnects in dataset circuits," IEEE Trans. Microwave Theory Tech., vol. 44, pp. 2495-2503, Dec. 1996.

[8] J. W. Bandler, M. A. Ismail, J. E. Rayas-Sanchez, and Q. J. Zhang, "Neuromodeling of microwave circuits exploiting space-mapping technology," IEEE Trans. Microwave Theory Tech., vol. 47, pp. 2417-2427, Dec. 1999.

[9] P. M. Watson and K. C. Gupta, "Design and optimization of CPW circuits using EM-ANN models for CPW components," IEEE Trans. Microwave Theory Tech., vol. 45, pp. 2515-2523, Dec. 1997.

[10] G. L. Creech, B. J. Paul, C. D. Lesniak, T. J. Jenkins, and M. C. Calcatera, "Artificial neural networks for fast and accurate EM-CAD of microwave circuits," IEEE Trans. Microwave Theory Tech., vol. 45, pp. 794-802, May 1997.

[11] A. H. Zaabab, Q. J. Zhang, and M. S. Nakhla, "A neural network modeling approach to circuit optimization and statistical design," IEEE Trans Microwave Theory Tech., vol. 43, pp. 1349-1358, June 1995.

[12] J. Lakshmi Narayana, Dr. K. Sri Rama Krishna and Dr. L. Pratap Reddy, "Performance Evaluation of Neural Models for the Analysis of GaAs MESFET", GITAM Journal of Information Communication Technology, Vizag, Vol. 01, pp. 31-41, 2008.

[13] Fang Wang, Vijaya K. Devabhaktuni, Changgeng Xi, Qi-Jun Zhang, "Neural Network Structures and Training Algorithms for RF and Microwave Applications," John Wiley & Sons, pp. 216-240, 1999.

[14] Xiu Ping Li & Jian Jun Gao, "Millimeter-wave Micromachined Filter Design by Artificial Neural Network Modeling Technique," International Journal of Infrared and Millimeter Waves, Volume 28, Issue 7, pp. 541-546, July 2007.

[15] Bian Wu, Wen Su, Shou-jia Sun, Chang-Hong Liang, "Novel Dual-Mode Bandpass Filter Using Slot-Line Square Loop Resonator," IEEE International Conference on Microwave and Millimeter Wave Technology (ICMMT), vol. 2 pp. 1-3, 2012.

[16] Manidipa Nath, Bhaskar Gupta, "Analysis of EM scattering in Waveguide Filter using Neural Network," International Journal of Electronics and Computer Science Engineering, ISSN-2277-1956, Volume 1, No. 2, pp. 639-642, 2012.

[17] R.E. Zich, M. Mussetta, F. Grimaccia, A. Gandelli, H.M. Linh, G. Agoletti, M. Bertarini, L. Combi, P.F. Scaramuzzino, A. Serboli, "Comparison of different optimization techniques in microstrip filter design," IEEE Asia-Pacific International Microwave Symposium on Electromagnetic Compatibility (APEMC), pp. 549-552, 2012.