Optimal Design of a Waveguide Bandpass Filter Using ANN-GA Algorithm

Manidipa Nath, Sudhabindu Ray[1], Bhaskar Gupta[1]

Abstract - **In this work design and optimization of EBG structure having multiple dielectric posts uniformly placed inside a rectangular waveguide is done to extract filter responses. Frequency response of BPF configuration using trained ANN model of multipost rectangular waveguide are studied and optimized using GA. The geometrical and positional dimension of post parameters are varied in accordance to the requirement of reflectance and transmittance of the filter.**

Keywords – **Dielectric post, Waveguide filter, Optimization, Scattering, Frequency response.**

I. Introduction

Filter design, synthesis and optimization to meet a predefined criterion decided by the user are a challenging task for design engineer or scientist. Microwave filters having broad bandwidth has a wide applications in communication receiver and several techniques are available in the literature [1-2] to meet the design specifications. EM software tools for analysis and synthesis of microwave passive devices are available and can be used to design and optimize waveguide filter structure up to certain accuracy.

Theoretical analysis of the multipost rectangular waveguide structure is made using the scattering theory based on Lattice Sum and T-matrix of circular cylinder [1-3].A Matlab code has been generated using the theory and used to train and test an ANN model of a rectangular waveguide structure having multiple dielectric posts inside it. The scattering reflectance and transmittance of trained ANN model of the structure under concern can be predicted.

Different combinations of dielectric posts inside rectangular waveguide are used to design the filter where the position and geometrical parameters of the posts are nonlinearly related with the reflectance and transmittance of the waveguide structure under concern.

ANN models follow the non linear circuit behaviour when properly trained and tested using the data obtained from the theoretical analysis.GA optimization techniques is used here with the ANN model of the same where the dimensions of the post parameters that decides the frequency response of the filter can be made optimal.

Manidipa Nath is with the faculty of ECE Department, AIACTR, Geeta Colony, Delhi 110031, E-mail: manidipa.deoghar@gmail.com.

[1]Sudhabindu Ray and Bhaskar Gupta are with the faculty of ETCE Department, Jadavpur University, 88, Raja S.C Mallick Road, Kolkata 700032, E-mail: sray.ju@gmail.com, gupta_bh@gmail.com.

The final optimized post parameters obtained from the ANN-GA model of the filter are verified from EM simulation. The filter is fabricated using the optimal dimensions of the waveguide and the dielectric posts. Measured frequency responses of the optimal filter are compared with the simulated response. The comparison tables show the usefulness of this technique for design and performance optimization of filters as a suitable alternative tool to commercial EM softwares.

II. Theory

Artificial Neural Networks (ANN) is a computational model based on biological Neural Networks (NN). It consists of an interconnected group of artificial neurons and processes information by a weighted sum approach. In most cases an ANN works as an adaptive system that changes its structure based on external or internal information that flows through the network during the learning phase. Being a non-linear statistical data modelling tool NN can be used to model complex relationships between inputs and outputs and can be trained to learn from observation and generalize by abstraction [1]. A Multi Layered Perceptron (MLP) is a network of neurons with weighted interconnections where each neuron uses a nonlinear activation function. A MLP model trained by a Back Propagation (BP) algorithm [2] is a standard computational tool for any supervised-learning function approximation process.

Design and modelling of filters in RF and Microwave frequency range [3-5] requires evaluation of circuit performance in an iterative way and implementation of optimization based algorithm.

ANN is nowadays popular as efficient alternatives to conventional computational models like numerical modelling or analytical methods having highly repetitive computational process. ANN modelling techniques allows very fast evaluation resulting in a simpler computation process without sacrificing accuracy. Thus the technique has greater potential in the analysis of various problems in electromagnetism.

In this work, the neurons are properly trained to model the scattering reflectance and transmittance from multiple dielectric post embedded in rectangular waveguide. The universal approximation theorem [3] states that there always exists a three layer MLP NN that can approximate any arbitrary nonlinear continuous multi-dimensional function to any desired accuracy. This forms a theoretical basis for employing NN networks to approximate RF/Microwave circuit and systems, as well for this work.

III. MULTIPOST RECTANGULAR WAVEGUIDE

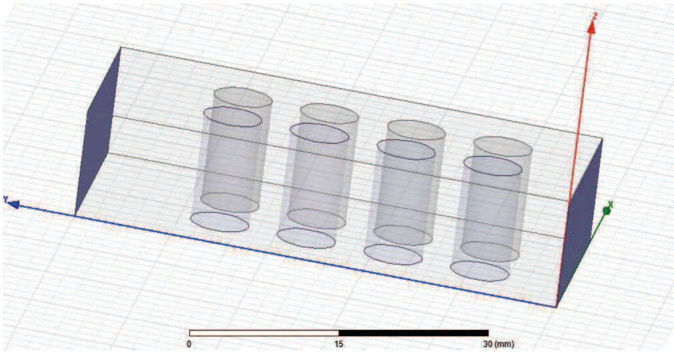


Fig. 1. 3D view of the filter structure having eight dielectric posts inside rectangular waveguide

Several techniques have already been applied for analysing the scattering behaviour of rectangular waveguides having circular dielectric posts as discontinuities [1]. In the present problem ANN technique has been used for non-linear modelling of the frequency response of a three dimensional rectangular waveguide at X band which is having eight circular dielectric cylinder uniformly placed. The systematic design of the ANN and proper training procedure is required to model the non linear relationship of post parameters with the frequency response characteristics of the filter structure under consideration. The scattering properties of the vertical dielectric posts are analyzed, the scattered fields are theoretically formulated and computed based on image theory [2] using Lattice Sum and the Transition matrices (T-matrix).

Analysis results have been used to generate S parameter data for the waveguide structure having eight dielectric posts symmetrically arranged and are utilized to train the ANN model of the same. The trained ANN model is utilized to optimize the reflectance and transmittance of the waveguide structure using a proper fitness function using Genetic Algorithm (GA).

Changing the geometrical dimensions of the posts the desired reflectance and transmittance of the waveguide structure can be achieved and ANN-GA algorithm is used to optimize the frequency response and bandwidth of the filter. Finite Element Method (FEM) is used to verify the frequency response characteristics of the optimized filter structure.

The reflection and transmission matrices of the filter structure having eight dielectric posts arranged uniformly inside rectangular waveguide is derived in closed form [3] using the Lattice sums and the T-matrix of a circular cylinder in free space. ANN model of the multipost waveguide structure is developed at X band with suitable network architecture where the parameters used as inputs of the proposed NN model are

i) the number of dielectric posts,

ii) positions of the dielectric posts w.r.t. waveguide axis

iii) dielectric constant of the post material.

The outputs are magnitudes of S11 and S21. The ranges of input parameter used for ANN model are shown in table I.

The parameters required to design an ANN are the range of initial weights, initial values of learning rate, momentum rate, hidden node number and the network architecture. The learning rate of NN is sensitive to the initial value of the weight vector. The initial weights are generated using a uniform random number generator in the finite range. The network architectures are described by the number of hidden layer, the number of nodes in each layer. The number of hidden nodes required to train the NN is minimized where the number of epochs is reduced to less than 50%. The result is an improvement in the convergence speed of the algorithm.

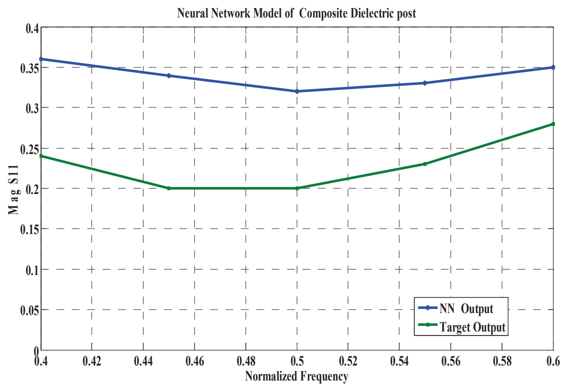
IV. DESIGN OF ANN MODEL

A four layer MLP is used to model the scattering from eight dielectric posts in rectangular waveguides. The post positions are chosen to be symmetric w.r.t. x axis for a suitable application of the structure as filter. The input layer has four independent neurons which represent four input parameters normalized with their maximum value. For this purpose of input layer modelling two post positions (the other two are symmetrically placed) relative to y axis of the waveguide, dielectric constant of the post material, diameter of the posts are taken as inputs. The two hidden layers are chosen having 48 and 28 number of neurons respectively. The output layer has two neuron representing Mag (S11) and Mag (S21). The waveguide used here is WR-90 (22.86 mm x 10.16 mm.) for the X band frequencies.

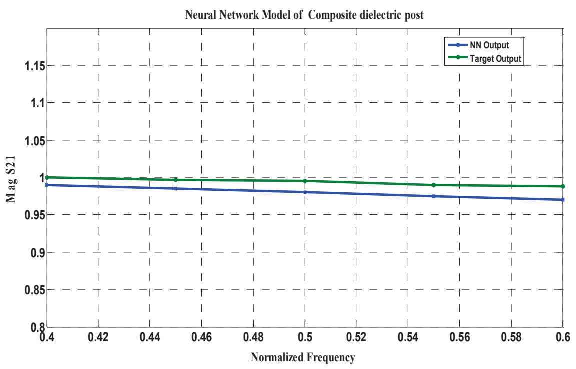
The training data generated from the scattering theory has a normalized range from –1 to +1, the bipolar sigmoid function has been chosen as activation function.

The ANN model is trained using 860 data sets involving various combinations of normalized input parameters. The resulting mean-squared error between the network's output and the target value over all the training pairs are minimized. Here the gradient decent back propagation model is used for minimizing the error function.

The testing of the ANN model is done using the theoretically computed data over the X band so that the trained and tested ANN model can follow the scattering behaviour of multipost waveguide within a reasonable accuracy. After proper training the average relative error is found to be 0.1 for Mag (S11) and 0.05 for Mag (S21) over a set of test data spanning the entire X band of frequencies and different values for the position and dielectric constant of the dielectric posts, which have not been used in the training process. The frequency response plots of theoretically computed S parameters with that obtained using ANN model of the same is compared and shown in figure 2(a) and 2(b).The accuracy of the trained ANN model is shown in table II.



(a)



(b)

Fig. 2. Comparison of response of the NN model with the computed values of magnitude of reflectance and transmittance of eight dielectric posts embedded in rectangular waveguide

(a) Comparison of computed Mag S11with that of the NN model

(b) Comparison of computed Mag S21with that of the NN model

V. Optimization Using GA

In this work determination of the set of post parameters used for optimization of the filter is done and a suitable fitness function is utilized for the process of optimization of reflectance and transmittance of the multiple dielectric post loaded waveguide structure as obtained from its trained ANN model. Finally different fitness functions are studied and a suitable function has been implemented for the optimization of the S parameters of the waveguide structure having eight dielectric posts.

The scattering reflectance and transmittance of the waveguide filter obtained from its ANN model is fed to the GA optimizer to obtain the best achievable filter performance. In other words the overall reflectance and transmittance of the ANN model of the waveguide filter is considered for best broadband performance and GA is utilized to maximize the transmission and minimize the reflection over the X band. In the process of optimization the dimension of the posts and their relative positions are altered in order to get the maximum pass bandwidth of the waveguide bandpass filter where fabrication limitations are also considered.

The multilayered ANN integrated with the GA has been applied to optimize the filter bandwidth and improve the insertion loss as far as possible within the practically achievable fabrication accuracy of the filter structure.

In this optimization the fitness function used is minimize $\sum_{Freq}(W_1 S_{21} + W_2 / S_{22})$ where W1=W2=0.5 are the weight parameters and 80 frequency points are taken within the frequency band from 8.0-12.0 GHz. The fitness function is used for GA optimizer in order to maximize the bandwidth of the filter and minimize the return loss. The GA convergence plot is shown in figure 3 where the convergence has been achieved within 50 iterations.

VI. Simulation

The ANN model of the waveguide filter having four layer two post structures is optimized for maximum passband and minimum insertion loss using GA. The band width of the optimized filter as obtained from ANN-GA model is 9.8 – 12.0 GHz with a return loss better than -10 dB over this range of frequencies. The filter geometry using X band waveguide with eight acrylic rods arranged in four layer configuration is shown in figure 4. The optimized filter structure is simulated using HFSS and the simulation results of the waveguide filter are shown in figure 5. The ANN-GA optimization result and EM simulated results are compared and a good match is obtained which verifies the suitability of the optimized ANN-GA model of the filter. Optimized frequency response of the waveguide filter using ANN-GA model has been verified by HFSS, a commercially available EM analysis software tool based on FEM. The dimension of the waveguide and optimized parameter values for the dielectric posts are obtained from the ANN-GA model of the filter are compared with that of the EM simulation and tabulated in table III. The optimum performance of the filter structure having eight dielectric posts inside rectangular waveguide in terms of S parameters or the frequency response of its ANN-GA model within the frequency band of interest and simulated frequency response using EM software is tabulated and shown in table IV.

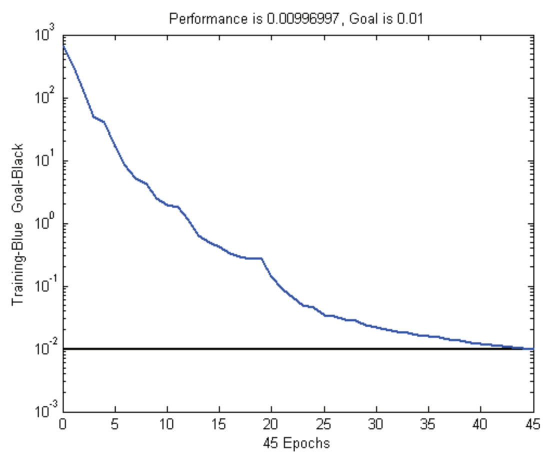


Fig. 3. GA Optimization convergence plot

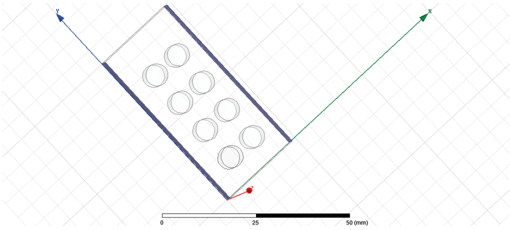


Fig. 4. Simulation model of the waveguide filter (eight post in four layer configuration)

The optimized parameter values for the position and dimensions of eight posts inside rectangular waveguide as obtained from the ANN-GA model are used for fabrication of the optimized waveguide filter and are tabulated in Table V.

VII. Fabrication of Optimal Filter

The dimensional accuracy as well as positional accuracy of the posts inside the waveguide is essential for mechanical point of view. The accuracy of the placement of dielectric posts in both lateral and longitudinal direction is required to get the desired frequency response of the optimum waveguide filter. As the interactions of E field with the posts inside the waveguide depends on the geometrical positions of the posts under concern, in addition to the material parameters of the same precautions are required for alignments as well as uniformity of the posts used for fabrication of the filter. The fabricated filter has been integrated with suitable adaptor and the frequency response of this filter such as return loss and transmission characteristics in terms of scattering parameters has been measured using VNA over the full X band.

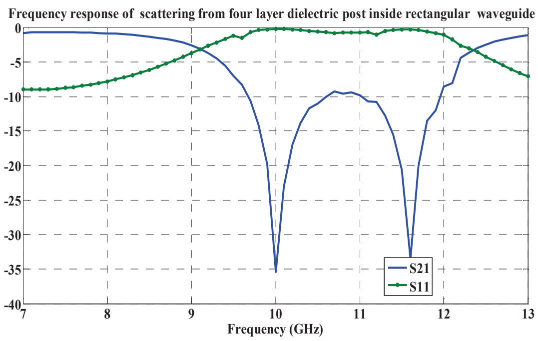


Fig. 5. Optimized frequency response of the waveguide filter

TABLE I
Range of Input Parameters used for ANN_GA model of the Multipost Rectangular Waveguide

Parameters	Range
Dielectric constant of the post	2.0-12.0
Dielectric post diameter (mm.)	1.0 -10.0
Post spacing between two successive posts (mm)	1.0- 5.0
Post spacing between two successive layer (mm)	2.0- 6.0
Number of posts	02- 12

TABLE II
The Accuracy of Developed ANN Model

Eight dielectric post		
Mag S11	Training(error) 0.1	Testing (error) 0.2
Mag S21	0.05	0.07

VIII. Measurement of Optimal Filer

The fabricated filter shown in figure 6 has been tested using VNA as shown in figure 7(a) and (b). The S21 and S11 of the filter over the X band are measured and are shown in Fig. 8.

The measured frequency response of the filter shows a bandpass characteristics from 9.9 GHz -12.7 GHz. In other words more or less 26.0% fractional bandwidth is achieved in the X band with an insertion loss of 3.0 dB over the frequency band. The measured performance is compared with the simulated performance of the filter under consideration and the results are tabulated in table VI.

The return loss is higher than expected as the fabrication inaccuracies like proper alignments and maintaining exact spacing of posts inside the waveguide is difficult from the mechanical point of view. It has been checked manually and tried to rectify for maximum possible accuracy for fabrication, but the available infrastructure does not support the same as required for achieving the target accuracy for the desired frequency response of this filter.

TABLE III
Comparison of Optimized Post Parameters of the Waveguide Filter (from ANN-GA model and EM Simulation Model)

Filter Parameters	ANN_GA model	EM Simulation
Post position from edge	7.0mm	7.0mm
Post diameter	6.0 mm	6.0 mm
Post permittivity	6.0	6.0
Post spacing	2.0 mm	2.0 mm
Number of posts	Eight	Eight

It is observed that the structure can work as band pass filter when specific post parameters are chosen in the frequency band of interest. This type of model is very useful in optimization problems where a fast and accurate response is required.

GA is used to optimize the frequency response performance of the filter under consideration using suitable fitness function. Finally the optimized design of waveguide filter is verified using EM simulation. The dimensions of post parameters from ANN_GA model is compared with that of the simulated dimensions and tabulated in table IV. The fabricated filter is characterized using VNA and measured frequency response is compared with that of the simulated results. Table VI shows a comparison table of simulated and measured frequency responses of the waveguide filter under concern.

The usefulness of the ANN-GA modelling technique in microwave filter design and optimization is illustrated practically and can be used for design optimization of other filters having different specifications in microwave frequency ranges.

TABLE IV
COMPARISON OF THE FREQUENCY RESPONSE OF THE FILTER (FROM ANN-GA MODEL AND EM SIMULATION MODEL)

Filter Parameter	ANN-GA model	Simulation model
VSWR BW	9.5–12.0 GHz.	9.8-12.0 GHz.
I.L. (dB)	1.0 dB	1.0 dB

TABLE V
POST PARAMETERS USED FOR FABRICATION OF THE FILTER

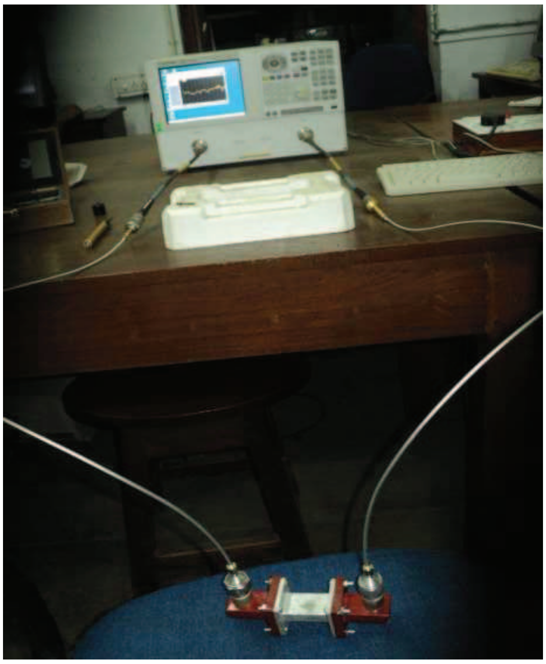
Parameter	Value
Waveguide	WR-28
Frequency Range	8.0-12.0 GHz.
Dielectric post diameter	6.0 mm
Dielectric post height	10.16 mm
Dielectric constant of post	6.0 (acrylic)
Spacing between two successive dielectric posts	2.0 mm

TABLE VI
COMPARISON OF SIMULATED AND MEASURED PERFORMANCE OF THE WAVEGUIDE FILTER

Filter Parameter	Simulated (eight post)	Measured (eight post)
VSWR BW	2.3 GHz	2.8GHz
I.L.(dB)	1.0dB	3.0dB

Fig. 6. Fabricated waveguide filter

(a)



(b)

Fig. 7. Measurement setup of the waveguide filter:
(a) Reflection measurement; (b) Transmission measurement

IX. DISCUSSIONS

The fabrication process of the waveguide filter involves complicated mechanical steps. This fabricated filter is very difficult to measure for fabrication in accuracies like the position of the posts, their relative gap and alignment. Again insertion of dielectric rod inside hollow waveguide w.r.t. the axis of waveguide creates some thin air gap at metal-dielectric junction and accurate modelling is required in order to model this imperfection which will be reflected in the final response as a loss term in reflectance and transmittance. This can be minimized using conducting glue at the air dielectric interface and characterizing the effect of the glue on overall performance of the filter. The verification process can be extended for the other frequency bands (higher or lower) after proper optimization of the filter under consideration.

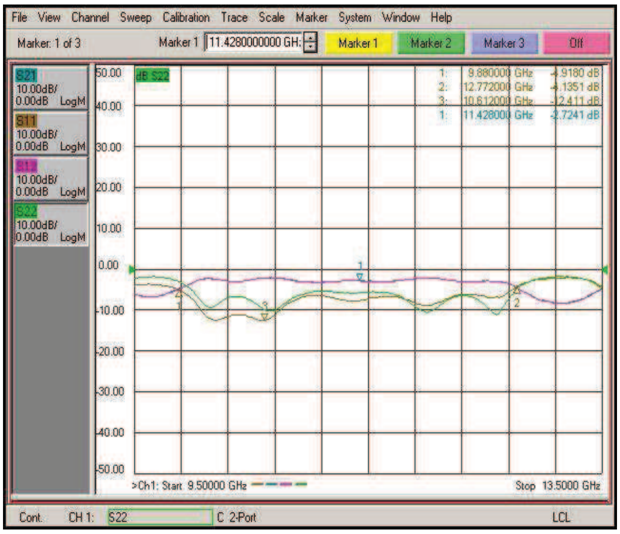


Fig. 8. Measured frequency response of the waveguide filter

X. CONCLUSION

Here ANN technique has been used for non-linear modelling of the frequency response of eight circular dielectric cylinder in a three dimensional rectangular waveguide at X band. The filter configuration is analyzed theoretically for the effect of EM scattering on frequency response performance of the same. The scattering analysis of a structure having eight dielectric posts inside rectangular waveguide has been carried out using Lattice sum and T–matrix method to generate S11and S21 data for the structure. S parameter data generated from this theoretical analysis are utilized to train the ANN model of the waveguide structure having eight dielectric posts in two layer configuration. An ANN model of the same is designed and 80% of the theoretically generated data are used for proper training of the ANN. Rest of the data generated is used for testing the model for the required accuracy.

REFERENCES

[1] K. Yasumoto, H. Jia, *Electromagnetic Theory and Applications for Photonic Crystals*, Chapter 3, vol. 103, pp. 123-190, CRC Press, 2005.

[2] K. Yasumoto, N. Koike, H. Jia and B. Gupta, “Analysis of electromagnetic bandgap based filters in a rectangular waveguide,” *IEICE Transactions*, vol. E89-C, no. 9, pp. 1324-1329, September 2006.

[3] J. Zhang, K. C. Gupta and V. K. Devabhakuni, “Artificial neural networks for RF and microwave design-from theory to practice,” *IEEE Trans. on MTT*, vol. 51, no. 4, pp. 1339-1350, April 2003.

[4] Q. J. Zhang, K. C. Gupta, *Neural Networks for RF and Microwave Design*, Chapter 3, Artech House, July 2000.

[5] H. Kabir, Y. Wang, M. Yu and Q. J. Zhang, “Application of artificial neural network techniques in microwave filter modelling, optimization and design,” *PIERS Online*, vol. 3, no. 7, pp. 1131-1135, 2007.