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OPTIMIZATION OF WAVEGUIDE INTERDIGITAL FILTER USING PSO AND ANN

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ABSTRACT

In this paper theoretical design and optimization of VSWR BW of a waveguide based Inter-digital filter using PSO-ANN algorithm is highlighted. The objective of this paper is to focus on use of the trained ANN model coupled with the particle swarm optimization (PSO) algorithm to synthesize and optimize an waveguide based inter-digital filter using resonating bars alternatively short circuited. Design, synthesis and optimization process is compared with the results obtained from EM simulation which is also compared from the same obtained experimentally. The design of a waveguide based Inter-digital filter using rectangular bars as its resonator elements is done using traditional synthesis process. Capacitance values of the resonators are evaluated using an Artificial Neural Network (ANN) model of the same with the geometry parameters of resonators as its inputs. Particle swarm optimization (PSO) algorithm is utilized to optimize the dimensional parameters of the resonators in order to obtain inter-resonator coupling coefficient values that can be used for the design of the broadband filter. The aim of the present research work is to design and optimize waveguide based inter-digital filter having rectangular bars as resonators for broadband VSWR BW. Electro-Magnetic simulations are performed using the theoretical design of the waveguide Inter-digital filter structure and compared for accuracy of the design and optimization process adopted here. The simulation results are in good agreement with those obtained using the ANN/PSO algorithm. The optimized design of the filter is developed by practical implementation in hardware and further characterized. Simulation and measurement results are compared to validate the design approach.

KEYWORDS: Rectangular Bar, Broadband, Filter, ANN/PSO, Inter-Digital, Capacitance

I. INTRODUCTION

Generally Inter-digital filters are preferred for its performance at the lower microwave frequencies. Inter-digital filters are metal resonators having the inter-element spacing related to its centre frequency and arranged as an alternative configuration between two ground planes.

The basic configuration of an inter-digital filter as shown in figure 1, is a group of coupled resonators in a metal housing. Each resonator has electrical length of $\lambda/4$ at the design frequency, but physically shortened by capacitance at the open end. The resonators are inter-digital in configuration, with the position of the open ends of the resonators alternating. The coupling between resonators is controlled by their separation.

Inter-digital BPF is compact due to coupling of adjacent resonators by the fringing fields. This particular configuration is used to design filters where wide VSWR BW (more than an octave) is required. The design dimensions are within the tolerance level of manufacturing process used for fabrication of the same due to reasonable spacing between resonator elements. The filter structure being self supportive can be fabricated with ease and loss due to dielectric material can be eliminated as the same is not required in general.

II. DESIGN APPROACH

Here design of rectangular waveguide based Inter-digital filter [1] is considered where frequency response of transmittance and reflectance of the same can be designed within 18.0-40.0 GHz. The two main techniques for design of inter-digital filters are those developed by Matthaei [1] and Wenzel [2]. Matthaei's design approach [1] is accurate and uses an approximation to the response of an ideal inter-digital filter which can be utilized for bandwidths of up to an octave [3-5]. The Matthaei's design process is easy to use and produces good results but extremely rigid and limits the designer's freedom to adjust filter dimensions. Wenzel's synthesis procedure [2] is exact and based on capacitance matrices and procedure involves complicated matrix manipulations.

Theoretical computations using equations relating the coupling factors and external Q of the structure capacitances can be used as alternative and flexible design procedure of the filter [3-5]. Furthermore, these equations aid visualization of the relationship between the physical structure of an inter-digital filter, its coupling factors and external Qs [1]. These equations are used as the basis for design and train the ANN model of the resonator elements of the filter. The values of the desired coupling factors and external Qs can be found from [6-8]

$$k_{mn} = \frac{\Delta w}{w_0 g_m g_n} \text{ and} \quad (1)$$

$$Q_E = g_0 g_1 w_0 \; / \; \Delta w \quad (2)$$

Where Δw is the desired BW, and the values of g_n are the component values of a conventional normalized low-pass filter prototype. The g_n values can either be calculated or obtained from standard filter tables [6].Once the desired values of the filter parameters are known mathematical relations can be used to realize these values. The required parameters of filter under consideration are shown in Table 1. The values of the capacitances can be determined from graphs and tables [6] or from electrostatic simulators.

The filter prototype values obtained using the coupling factors and external Q as given in Table 2**.** The inherent symmetry of inter-digital filters is due to symmetrical coupling coefficient and external Q values despite the fact that the prototype filter coefficients are not.

Matthaei chooses his sole design parameter and resonator impedances are assumed to be close to 76.0 ohm to obtain optimum resonator Q. The values used here are recalculated using Matthaei's equations and differ slightly from the results published [1] due to rounding errors. The impedances of all the resonators, except the first, were set to 76.0 W. The modified admittance ($Y_1 mod$) was set to 1/76.0 W by adjusting admittance of the first resonator ($Y1$) and the coupling capacitances are then calculated. The design procedure is flexible and it is easy to modify the structure by altering the dimensions of the resonators as long as the correct coupling factors and external Qs are realized.

This type of design is particularly valuable for tuning VSWR BW of filters. The external Qs and coupling factors are optimized for obtaining VSWR BW of the filter structure under consideration and any deviations from the desired values are removed by tuning the dimensions of the filter resonators.

The effect of design modifications on the filter dimensions can be predicted using the present design method. For a specific capacitance value, physical dimensions of the resonators can be computed theoretically for a particular cavity dimensions.

III. THEORY

Approximate design equations [4-6] for design of resonators of inter-digital filter are considered here to be sufficiently accurate for most practical applications. Design methods are related to the existing design data of Getsinger [2] which are useful for the design method adapted here. The conformal mapping technique based on fringing capacitances is used to compute the coupling coefficient of parallel-coupled TEM transmission line structure formed by two rectangular bars. The expressions for fringing capacitance by conformal mapping techniques are based on the procedure published by Getsinger [2] and are used to compute coupling coefficient for rectangular bars having width significant compared to thickness and inter-resonator spacing[2].

Curves are generated giving the even-mode fringing capacitance, odd-mode fringing capacitance, and the difference between odd- and even-mode fringing capacitances for wide ranges of thickness and spacing of rectangular bars centered between parallel plates. Simple formulas are utilized relating these capacitances to even- and odd-mode characteristic impedances of coupled rectangular bars**.**

The coupling capacitance for the physical geometry of inter-digital filter under consideration can be directly obtained graphically without solving the complicated equations associated with the theoretical solution. Figure 2 shows the curves relating the fringing capacitance with normalized spacing published by Getsinger [2]. These curves are used to compute graphically the capacitance of two rectangular bars for desired coupling for a particular geometry. Accuracy of the theoretically computed data is verified using EM simulation and experimental results of the developed filter. The measurement results are presented here to verify the accuracy of the theoretically computed coupling data.

One of the common elements in microwave integrated circuits (MICs) is the inter-digital capacitor. The theoretical analysis is used to generate training and testing data for the coupling capacitance of inter-digital resonators. ANN models [9-12] of the inter-digital resonators are designed trained and tested using the theoretically computed data. Trained ANN model for the waveguide filter as shown in figure 1 is realized and EM simulations are used to compute the frequency response of the same.PSO [13-14] has been applied for optimization of the physical dimensions of the resonators and in turn the VSWR BW of the filter structure under consideration.

IV. EVEN AND ODD MODE CAPACITANCE

The even and odd mode characteristic impedances and effective dielectric constant of the coupled rectangular bars are obtained from even and odd mode capacitance [1]. Dimensions of parallel-coupled lines are computed from the values of odd and even impedances from theoretical computations. Normalized self and mutual capacitance per unit length for all resonators of the structure under consideration are related with the physical dimensions of the same as well as spacing between them. For rectangular bars having small width approximate correction terms are used which is based on values of fringing fields due to parallel plate capacitance.

V. DESIGN

Electrical properties of coupled rectangular bars are characterized in terms of self capacitance per unit length of each bar with respect to ground and the mutual capacitance per unit length between adjacent bars. Even and odd mode characteristic impedance of coupled rectangular bars, even mode fringing capacitance, odd mode fringing capacitance and the difference between them for wide range of thickness and spacing of rectangular bars arranged between parallel ground plane are used to synthesis of the design of the filter.

The explicit design equations for the BPF are available in standard literature [3-4]. The Inverter admittance of each resonator is expressed by $\theta = \frac{\pi}{2}(1 - \frac{FBW}{2})$

Where, FBW is the fractional bandwidth and g_i represents the element values of a ladder type of low pass prototype filter with normalized cutoff frequency at $\Omega_c = 1$

The admittance is $Y = Y_1 / \tan\theta$, Inverter admittance of each resonator is expressed by

$$\frac{J_{i,i+1}}{Y} = \frac{1}{\sqrt{g_i g_{i+1}}} \quad \text{for i= 1 to n-1}$$

$$\frac{J_{n,n+1}}{Y} = \frac{1}{\sqrt{g_n g_{n+1}\omega}}$$

$$N_{k,k+1} = \sqrt{(\frac{J_{k.k+1}}{Y_A})^2 + \frac{\tan^2\theta_1}{4}} \quad \text{k= 1 to n-1}$$

$$M_1 = Y_A(\frac{J_{01}}{Y_A}\sqrt{h+1})$$

Self Capacitance, Ci (i = 1 to n) per unit length for the each line elements can be obtained from

$$\frac{C_0}{\varepsilon} = \frac{376.7}{\sqrt{\varepsilon_r}}(2Y_A - M_1)$$

$$\frac{C_1}{\varepsilon} = \frac{376.7}{\sqrt{\varepsilon_r}}[Y_A - M_1 + hY_A[\frac{\tan\theta_1}{2} + (\frac{J_{01}}{Y_A})^2 + N_{12} + \frac{J_{12}}{Y_A}]]$$

$$\frac{C_k}{\varepsilon} = \frac{376.7}{\sqrt{\varepsilon_r}}hY_A(N_{k,k-1} + N_{k,k+1} - \frac{J_{k,k-1}}{Y_A} - \frac{J_{k,k+1}}{Y_A}) \quad \text{for k =2 to n–1}$$

$$\frac{C_n}{\varepsilon} = \frac{376.7}{\sqrt{\varepsilon_r}}[Y_A - M_n + hY_A[\frac{\tan\theta_1}{2} + (\frac{J_{n,n+1}}{Y_A})^2 + N_{n-1,n} + \frac{J_{n-1,n}}{Y_A}]]$$

$$\frac{C_{n+1}}{\varepsilon}=\frac{376.7}{\sqrt{\varepsilon_r}}(2Y_A-M_n)$$

Mutual Capacitance, $C_{i,i+1}$ (i = 1 to n - 1) per unit length for the each line elements can be obtained from

$$\frac{C_{01}}{\varepsilon}=\frac{376.7}{\sqrt{\varepsilon_r}}(M_1-Y_A)$$

$$\frac{C_{k,k+1}}{\varepsilon}=\frac{376.7}{\sqrt{\varepsilon_r}}hY_A(\frac{J_{k,k+1}}{Y_A})$$

$$\frac{C_{n,n+1}}{\varepsilon}=\frac{376.7}{\sqrt{\varepsilon_r}}(M_n-Y_A)$$

h admittance scale factor

$$h=\frac{2C_{k-1,k}}{\varepsilon}+\frac{C_k}{\varepsilon}+\frac{2C_{k,k+1}}{\varepsilon}$$

The number of low pass prototype filter elements and their g values are determined. The band pass characteristics are evaluated theoretically using normalized cavity height h=0.2330 which is required for high unloaded Q factor of all resonators. The normalized self and mutual capacitances of resonators are computed using MATLAB for estimation of physical dimension of resonators and spacing between them. For the design of the filter under consideration 25 resonators with ripple value 0.5 dB is used.

The starting dimension for an inter-digital filter is the width of the housing, λ/4 at the operating frequency and other dimensions are interrelated. The resonant frequencies of coupled inter-digital resonators versus the distance d between resonators are computed**.** Inter-resonator coupling coefficient is used to compute the capacitance values that can be used to generate frequency response of S parameters within the frequency range of operation.

The resonators are rectangular bars, have cross-section 4.3 mm. x 0.43 mm. and are situated between metal walls separated by 20.0 mm. The resonators are 1.95 mm long so that the resonant frequencies of a single uncoupled resonator are at 29.0 GHz. The resonant frequencies of modes are nearly the same when resonators are far from each other. When the distance between them approaches to zero resonant frequencies change in an asymmetric manner. Electromagnetic Simulations using CST is done to verify the theoretical design of wave guide Inter-digital filter.

VI. ANN MODEL

ANN model of the rectangular bars are designed and trained using data obtained from Getsinger as shown in figure 2. The trained ANN model is based on data generated from quasi-static expressions for the capacitance of resonators using conformal mapping method. The input of the ANN model is mutual capacitance and self capacitance of the rectangular bars and output is the physical dimension of resonators. Inter resonator spacing and width of each resonator is computed using trained ANN model of the same. Finally the resonator dimensions and inter-element spacing are optimized using PSO algorithm and used for computation of frequency response of the waveguide Inter-digital filter under consideration.

The simulation result reflects that up to 30.0 GHz. there is a fair agreement between the inter-resonator capacitance values obtained from trained ANN model of the same. The computation of frequency response of S parameters of the filter is based on accurate prediction of inter-resonator capacitance values within the practical fabrication limitations. CST simulation results for the VSWR BW are comparable to that obtained from the ANN model of the filter as shown in figure 3.

VII. ANN-PSO ALGORITHM

Inter resonator coupling capacitance value is modified using PSO algorithm to maximize the VSWR BW of the Inter-digital filter. Starting with a desired value of capacitance, the PSO algorithm is used to search the solution space for the physical dimensions of the resonators and cavity parameters that will give the desired capacitance with some acceptable error. The values of the capacitance using the PSO search are either exactly equal or very close to the required values. The difference between the desired capacitance and the optimized values of the capacitance is a result of the stopping criterion used in the PSO search.

The optimized parameter values obtained from the PSO are not unique and depend on the random initialization. Objective of the optimization is to find the dimensional parameters of the resonators that can be used for computation of VSWR BW of the Inter-digital filter. During the search process only values that are within the specified range are used and there are constraints on the parameters values that are accepted as a valid solution.

During the synthesis process, the PSO algorithm will converge and the search process will be terminated if the difference between the desired capacitance value and the calculated (using the ANN model) capacitance value is less than or equal to an accepted error value. In this particular synthesis problem, an error value of 10^{-2} was used and the `output of the PSO algorithm are controlled by the accepted error value.

To verify the design approach, CST is used to obtain the S parameter for waveguide Inter-digital filter using resonator elements. Simulated frequency response of the filter is shown in figure 4 where average S_{11} is -10.0 dB and average S_{12} is -5.0 dB over the frequency range 18.5-40.0 GHz. The fabricated filter is shown in figure 5 and characterized for its frequency response using VNA. The measured frequency response of the developed Inter-digital filter is shown in figure 6 and is comparable to the simulated one except insertion loss introduced by the coaxial connector and fabrication inaccuracies. Simulation and measurement results show the suitability of the ANN-PSO algorithm for optimization of the waveguide Inter digital filter within the frequency range under consideration.

Table 1: Inter-Digital Filter Design Parameters

Parameter	Value
Order (number of resonators)	25
Centre frequency	29.0 GHz.
VSWR BW	22.0 GHz.(18.0-40.0 GHz.)
Pass band ripple	0.1 dB

Table 2: Prototype and Calculated Filter Values

Index	Prototype Value (g_n)	Coupling Factor (k_{mn})	External Q (Q_E)
0	1.0000		11.68
1	1.1681	0.07809	
2	1.4039	0.05886	
3	2.0562	0.05662	
4	1.5170	0.05882	
5	1.9029	0.07809	
6	0.8618		11.68
7	1.3554		

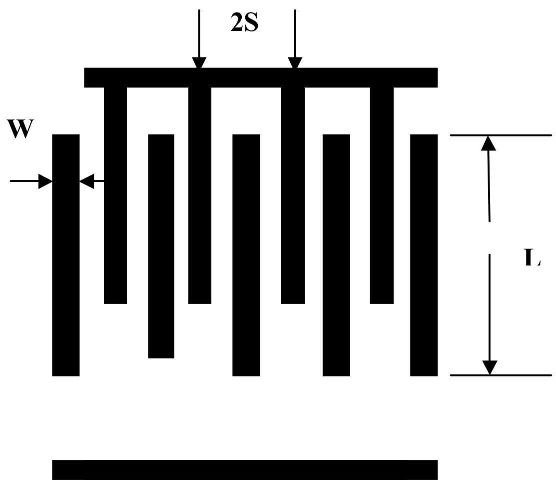

Figure 1: 2d View of the Waveguide Inter-Digital Filter

W = width of resonator, S = space between resonator, L= length of resonator.

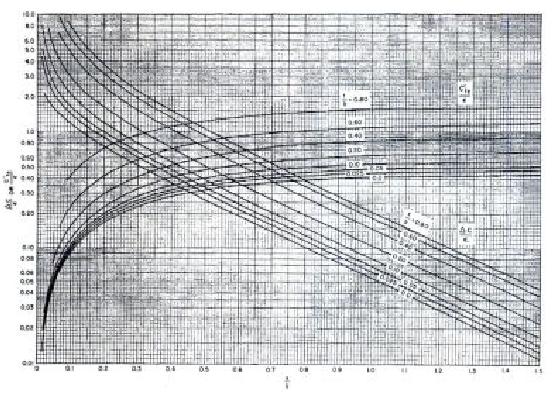

Figure 2

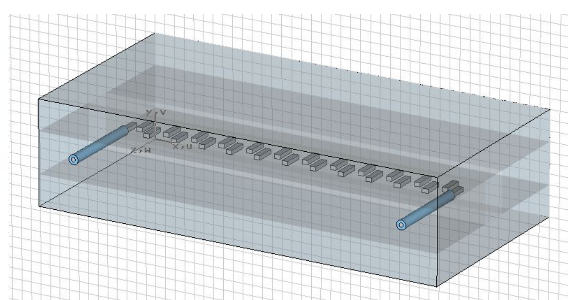

Figure 3

Figure 2: Getsinger Curves Relating Fringing Capacitance vs. Normalized width of Resonators

Figure 3: Simlation Model of the Waveguide Inter Digital Filter,Normalized Cavity Height 0.233,Thickness of Resonator 0.43 mm., Length of Resonator 1.95 mm., width of Resonator 4.3 mm

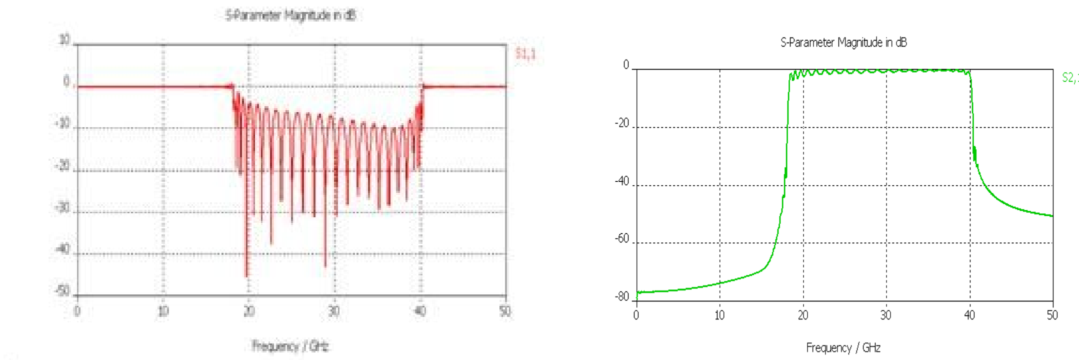

Figure 4: Simulation Results of S_{11} and S_{12} of the Inter-Digital Filter

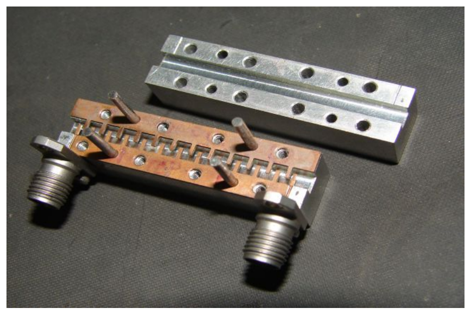

Figure 5: Optimized Waveguide Inter-Digital Filter

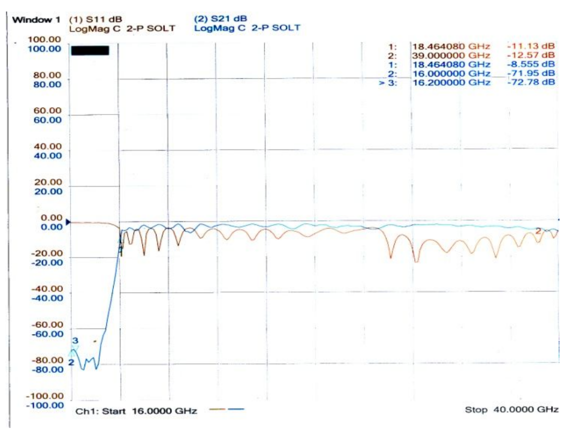

Figure 6: Measured Result (S_{11} and S_{12}) of the Waveguide Inter-Digital Filter

CONCLUSIONS

In this work waveguide based rectangular inter-digital filter is designed having frequency response of transmittance and reflectance from 18.0-40.0 GHz. The use of the particle swarm optimization (PSO) method in the synthesis of waveguide filter using inter-digital rectangular resonators is experimentally verified. The PSO algorithm, in conjunction with an ANN model of the resonators is successfully used to optimize the dimensional parameters of the resonators in order to obtain inter-resonator capacitance values that can be used for obtaining broad VSWR BW of the same.

The CST simulation results are in support of the proposed ANN/PSO model of the resonators. A CAD model for the resonators based on the design methodology presented in this article can be easily incorporated with existing software tools.

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