DESIGN OF SUSPENDED STRIPLINE COMBLINE FILTER WITH LOSSY RESONATOR

By

LIM CHIEW WEN

13853

FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

Universiti Teknologi Petronas

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

DESIGN OF SUSPENDED STRIPLINE COMBLINE FILTER WITH LOSSY RESONATOR

by

Lim Chiew Wen

A project dissertation submitted to the
Electrical & Electronics Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

Approved:

____

Dr. Wong Peng Wen
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

August 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

LIM CHIEW WEN

ABSTRACT

This paper presents both lossless and lossy filter synthesis design using a suspended stripline combline structure. With the evolvement in communication system, there is a growth in demand for compact, high-performance filter. A combline filter structure is able to reduce filter dimension. Lossy combline filter is proposed to overcome the conventional way of designing filter that made ideal assumptions and neglected the loss factor due to the finite Q of practical resonator. Incorporating loss into filter design leads to improvement for more accurate filter design parameters in practical realization. Both lossless and lossy four degree Combline filter using suspended stripline transmission has been designed fabricated and tested.

ACKNOWLEDGEMENTS

First and foremost, I thank God for it is through Him that all things are made possible.

Next, I would like to dedicate my outmost heartfelt appreciation to my supervisor, Dr. Wong Peng Wen who has been so kind and helpful to attend and advise me whenever I face difficulties throughout the research. He patiently guided me through the basics of microwave filter and never fails to encourage me to learn more. He did not give up on me or show any signs of frustration when my progress slacken for a period of time due to some personal problems faced back in my hometown. His tolerance and empathy has given me time to not only develop my knowledge in the fields of microwave filter design but also to mature mentally as an individual.

I also owe my deepest gratitude to Mr. Sovuthy Cheab, a graduate assistance of Dr. Wong, whose selfless time and care was sometimes all that kept me going. His unselfish and unfailing support has been my inspiration as I hurdle over all obstacles in this project. Likewise the rest of the team members, Mr. Soheatra Seoung and Mr. Chew Xiao Yan for their generosity and willingness in sharing the knowledge they possess. Selflessly, they provided me with study materials and notes to make sure I have better grasp of the theoretical concepts of the project. I am truly indebted to this team and I consider it an honour to be able to work with them.

Also, to my family members and friends who have given me so much encouragement and support – thank you! They have unconditionally loved me and walked with me through all hardships and storms in life. They are the reason I stand strong when I encounter difficulties and challenges in life.

Last but not least, this thesis would not have been possible unless my university, University Teknologi Petronas (UTP) and my sponsor, JPA have given me the opportunity to undergo my undergraduate studies. It has been an eye-opening journey so far and I thank the omnipresent God again for that.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

TEM – Transverse Electromagnetic

ADS – Advance Design System

AWR – Microwave Office

CAD – Computer Aided Design

MHz – Megahertz

GHz – Gigahertz

CHAPTER 1
INTRODUCTION

1.1 Background

Microwave filtering devices are gaining much importance as one of the main components in communication system. With the advancement of its diverse applications: from entertainment via satellite television, to civil and military radar systems, the requirements for such devices are becoming more stringent [1]. The main purpose of these microwave filters is to distinguish between desirable and undesirable signal frequencies in the system. Filter consists of two-port network and when it is connected between a source and a load, the filter allows power from the source within certain frequency bands to be transmitted to the load, in the meantime preventing power from passing to the load that is of other frequency bands. Thus, transmission of wanted signal frequency and rejection of unwanted frequencies are made possible. There are four types of filters namely; low-pass filter, high-pass filter, band-pass filter, and band-stop filter [2].

In microwave filter designs, filters can be created as lumped or distributed elements circuits and can be brought to fruition in various transmission line structures [4]. Transverse Electromagnetic (TEM) is a type of transmission line with its electric field being orthogonal to the magnetic field, and both fields are orthogonal to the direction of propagation. Examples of the available types of transmission modes of TEM are as shown in Figure 1.

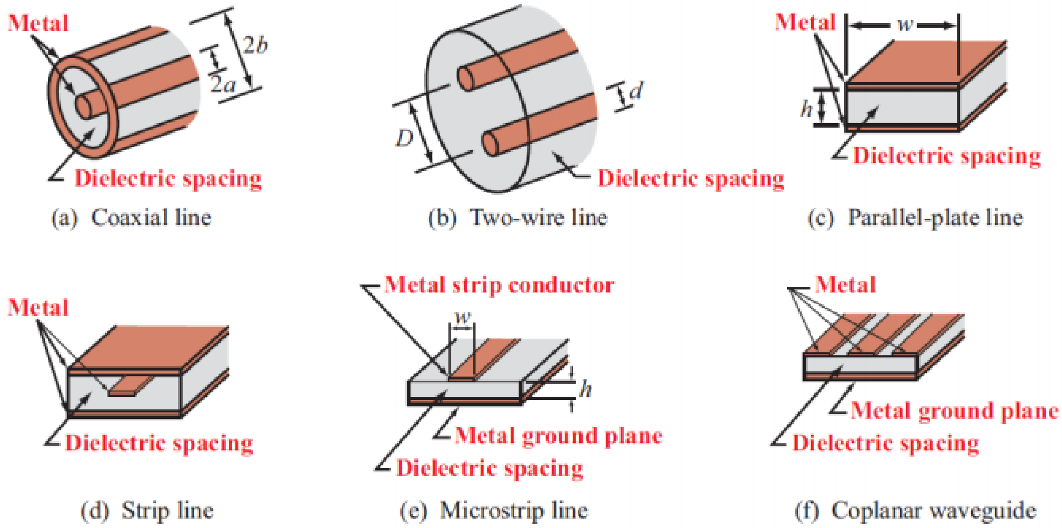


Figure 1: TEM transmission lines

Most common topology for a Transverse Electromagnetic (TEM) filter is the interdigital filter that possesses the advantages of a broad stopband and highly symmetrical frequency response [3]. However, the practical realization of this filter requires a relatively high resonator Q factors which results in the increase in volume of the filter. The combline filter on the other hand, is capable of overcoming these disadvantages with the expense of a slightly asymmetrical frequency response. Size reduction is possible due to capacitive-end loading of the resonator in combline filters. The following table summarizes the characteristics between interdigital and combline filter.

Table 1: Comparison between Interdigital and Combline Filter

	Interdigital Filter	**Combline Filter**
Properties	Broad stopband	Broad stopband
	Highly symmetrical frequency response	Slightly asymmetrical frequency response
	Physically large with resonators of quarter wavelength long (90°)	Physically compact as resonators with shorter than quarter wavelength (±50°)

	Large separation gap for narrow bandwidth	Resonators are closer together
	Tuning screws on alternate opposite	Tuning screws on same side

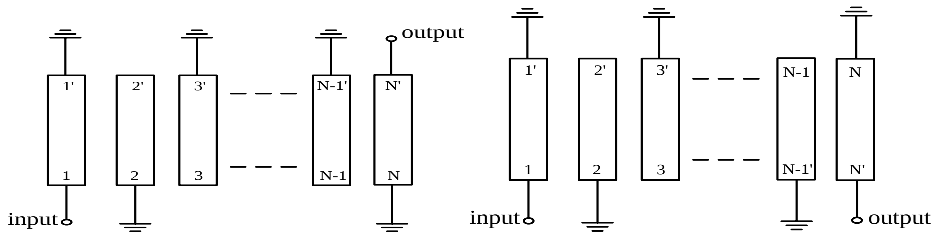


Figure 2: Interdigital Filter for N-even and N-odd

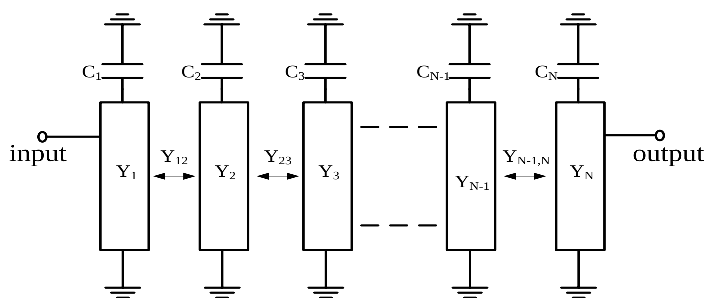


Figure 3: Combline Filter

This project involves procedures to design a lossy filter using suspended stripline combline topography. This project will start off with the analysis and synthesis of an ideal combline filter and proceeds to design the ideal filter using Advance Design System (ADS) software. The project then moves on to the analytical analysis and theoretical modeling of lossy combline filter before the design model is developed in Microwave Office (AWR) software. The design is then sent for prototype fabrication to be tested.

1.2 Problem Statement

Conventional design technique of combline filter does not take into consideration the loss factor due to the finite Q of practical resonator. Microwave engineers have been using direct synthesis of ideal microwave filter with the assumption that the filters are lossless. However, this is not the case of practical filters in reality because no finite device can produce ideal or infinitely selective amplitude. This leads to inconsistency in practical response as compared to the stimulated ideal response, which eventually affects the filter design accuracy.

1.1 Objectives and Scope of Study

This paper is devoted to develop design techniques, which enable filters to approach stimulated response theory as closely as possible. The main aims of this paper are:

- To synthesize a lossy combline prototype network
- To design the circuit using CAD tools
- To fabricate and measure the filter prototype

To realize this project, it is essential for one to understand the various analytical models and design parameters that are applicable in the process of filter designing. Having grasp of the basics, the scope of study also covers a deeper insight into characteristics of combline filters and the loss factors. This project also requires the knowledge about CAD tools to construct and stimulate the filters designed

CHAPTER 2

LITERATURE REVIEW AND THEORY

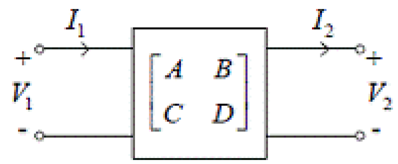
Microwave is defined as electromagnetic waves with frequencies ranging from 300MHz to 300GHz [4]. To control the frequency response, filters are used to provide transmission within the passband and to make sure attenuation occurs in the stopband of the filter. Microwave filter designs can be created either as lumped or distributed elements circuits which then to be realized in one of the types of transmission line structures [4]. Nevertheless, the most basics and fundamental approach to design microwave filter still lies in the realm of lossless lumped element microwave filter theory [5]. Regardless of the eventual physical realization, the design of lumped lowpass prototypes is the building blocks for the general synthesis of filters.

However, the realization of lumped elements of microwave filters at high frequencies is usually not possible because the wavelength is relatively short as compared to the dimensions of the circuit elements. This will eventually create losses due to the radiation from the elements and the interconnection between elements that act as parasitic element. Besides that, when sharp rejection is the concern, it is not preferable due to Q factor limitation [6]. According to Hunter [3], the resonator Q factor is proportional to the number of resonator used. Having said that, a filter with high selectivity will have its Q factor increase along, which leads to the bulking of filter's physical size. Consequently, lumped elements are transformed into distributed elements because lumped element theories alone would not suffice when we increase frequency into the microwave spectrum [3]. One such distributed element filter is combline filter. Matthaei was the first to introduce combline filter in 1964 [7]. Zakaria et. al. [1] put forward that a combline filter comprises an array of resonators aligned in parallel with one end short-circuited while the other end is connected to a loading capacitor. Anurag [6] further elaborated that the fringing fields between the resonator lines achieve the coupling effects of the filter. Combline filters are claimed to:

- have compact structure,
- easy to design,
- possess excellent stopband,
- able to have steep cutoff on high side of passband,
- have high selectivity features,
- maintain adequate coupling
- post-manufacturing tuning capabilities.

To improve selectivity in filters many research is focused on achieving smaller size filters with improved performance. The adaptive predistortion technique is about optimizing filter elements and assumes no change in filter topology [8]. This will eventually result in degraded return loss performance. Non-reciprocal devices are then used to compensate the loss. This however will cause the bulking in physical size. Another approach by Guyette, Hunter and Pollard [9], [10] is the application of lossy circuit extraction techniques. In this method, non-uniform dissipation is used along with added loss modified topology, which results in improvement in response and return loss. However, this synthesis method is only applicable in symmetrical filter networks that are limited to filters with even and odd mode analysis. Incorporation of loss factor in calculations for filter designing is essential to achieve a narrower difference between theoretical value and practical parameters.

When a network consists of two ports (eg: filters) and is assumed linear, with no internal independent sources, the transmission or transfer parameters can be obtained as follow:



where

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

and

$$A = \left.\frac{V_1}{V_2}\right|_{I_2=0}$$

$$B = \left.\frac{V_1}{I_2}\right|_{V_2=0}$$

$$C = \left.\frac{I_1}{V_2}\right|_{I_2=0}$$

$$D = \left.\frac{I_1}{I_2}\right|_{V_2=0}$$

Figure 4: Two-port network with ABCD parameter

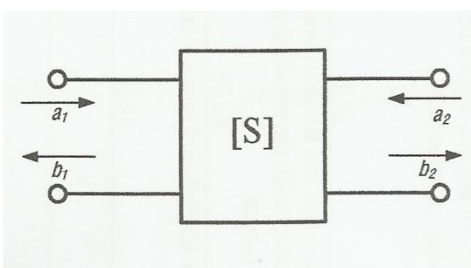
A -- Forward Voltage Gain

B -- Forward Transfer Impedance

C -- Forward Transfer Admittance

D -- Forward Current Gain

A representation that conforms with direct measurements, to the idea of incident, reflected and transmitted waves, is given by scattering matrix.



where

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

and

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$$

$$S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$$

$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$$

$$S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$

Figure 5: Two-port network with S paramenters

S_{11} -- Input Reflection Coefficient

S_{12} -- Reverse Gain

S_{21} -- Forward Gain

S_{22} -- Output Reflection Coefficient

The general transmission line transfer matrix is as follow:

$$[T] = \begin{bmatrix} \cosh(\gamma\ell) & Z_o \sinh(\gamma\ell) \\ Y_o \sinh(\gamma\ell) & \cosh(\gamma\ell) \end{bmatrix}$$

$$where\ \gamma = \alpha + j\beta$$

$$and\ \ \alpha = \alpha_c + \alpha_d\ ;\ \ \beta = \frac{\theta}{\ell}$$

Attenuation in a transmission line is due to finite conductivity associated with conductor loss (α_c) or lossy dielectric, also known as the dielectric loss (α_d). Attenuation by conductor loss depends on the field distribution in the line and is determined by taking into account the penetration of magnetic flux into each conducting surface that causes the incremental inductance. Thus, it is to be evaluated on an individual basis for each type of transmission line. Meanwhile, attenuation due to lossy dielectric can be obtained from the propagation constant if the line is homogeneous dielectric. General expression for propagation constant is defined as:

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$$

Using complex dielectric, propagation constant equation can be defined as:

$$\begin{aligned} \gamma &= \alpha_d + j\beta \\ &= \sqrt{k_c^2 - k^2} \\ &= \sqrt{k_c^2 - \omega^2 \mu_0 \epsilon_0 \epsilon_r (1 - j\tan\delta)} \end{aligned}$$

From the propagation constant equation above, dielectric loss, α_d is given as follow:

$$\alpha_d = \frac{k^2 \tan\delta}{2\beta}$$

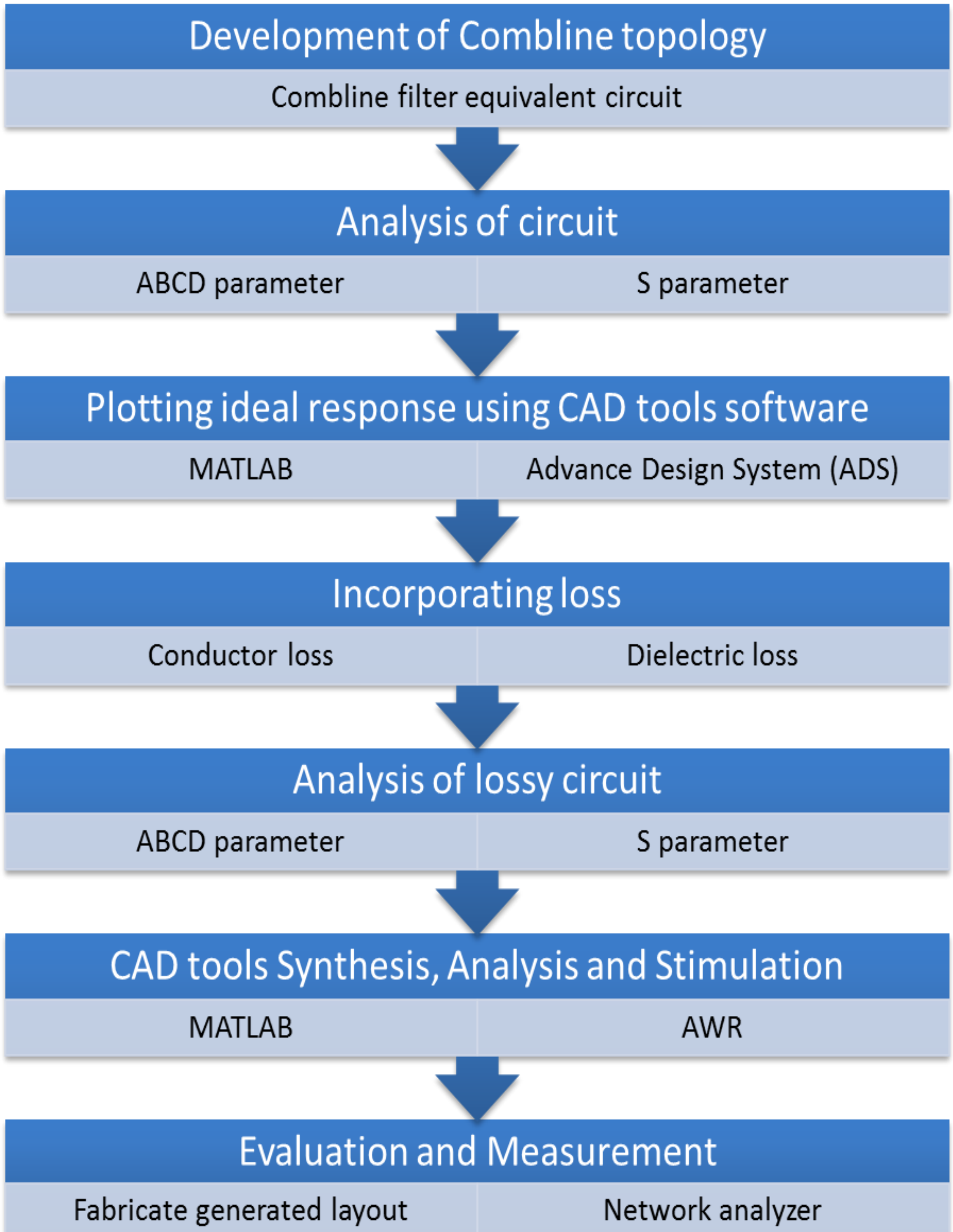
A suspended stripline circuit consists of a metal strip conductor that is sandwiched between two parallel metal ground planes with dielectric substrate spacing in between. The characteristic impedance of a suspended stripline transmission line is dependant on the width of the strip, the thickness and relative permittivity of the substrate. Suspended stripline is non-dispersive, has no cut-off frequency and is claimed to be able to provide:

- high Q-factor
- wide bandwidth
- good temperature stability
- enhance noise immunity

CHAPTER 3
METHODOLOGY AND PROJECT WORK

3.1 Research Methodology and Project Activities

For a starter, the idea is to get initial view on the overall microwave filter system and theory. The basics and fundamentals of microwave filter designing are studied. After through literature reviews, the combline filter topology is developed alongside with its equivalent circuit. Circuit is then analyzed to identify its characteristics using ABCD parameter and S parameter. Next, with the help of Computer Aided Design (CAD) tools software; mainly MATLAB and Advance Design System (ADS), ideal response of combline filter using ideal transmission line is plotted. Finally, the effect of losses in real circuit element is incorporated into the calculations. After the synthesis of the lossy combline filter network, the filter is yet again designed using CAD tools for stimulation. Only then the measurements are sent for prototype fabrication and lastly, a network analyzer is used to evaluate and verify the validity of the proposed technique. The impact of a lossy combline filter design is studied and comparisons are made between an ideal filter designs with lossy filter designs. The significance of a lossy filter design is then concluded.


Development of Combline topology
Combline filter equivalent circuit
Analysis of circuit
ABCD parameter
S parameter
Plotting ideal response using CAD tools software
MATLAB
Advance Design System (ADS)
Incorporating loss
Conductor loss
Dielectric loss
Analysis of lossy circuit
ABCD parameter
S parameter
CAD tools Synthesis, Analysis and Stimulation
MATLAB
AWR
Evaluation and Measurement
Fabricate generated layout
Network analyzer

3.2 Project Key Milestones

Phase 1: Studies on the basics and fundamentals of microwave filter designing.

- Thorough studies are done to grasp a better understanding on the theoretical analysis and synthesis of microwave filter technology and designing. Past researches and papers are reviewed to obtain a better insight.

Phase 2: Synthesis of a lossy combline filter

- Circuit derivation of a lossless combline filter is carried out with application of ABCD matrix and S-parameters approach. Ideal case responses are then plotted using MATLAB software.
- Incorporation of lossy calculations to design the filter to enable a more accurate stimulated response that is comparable to the practical response in reality

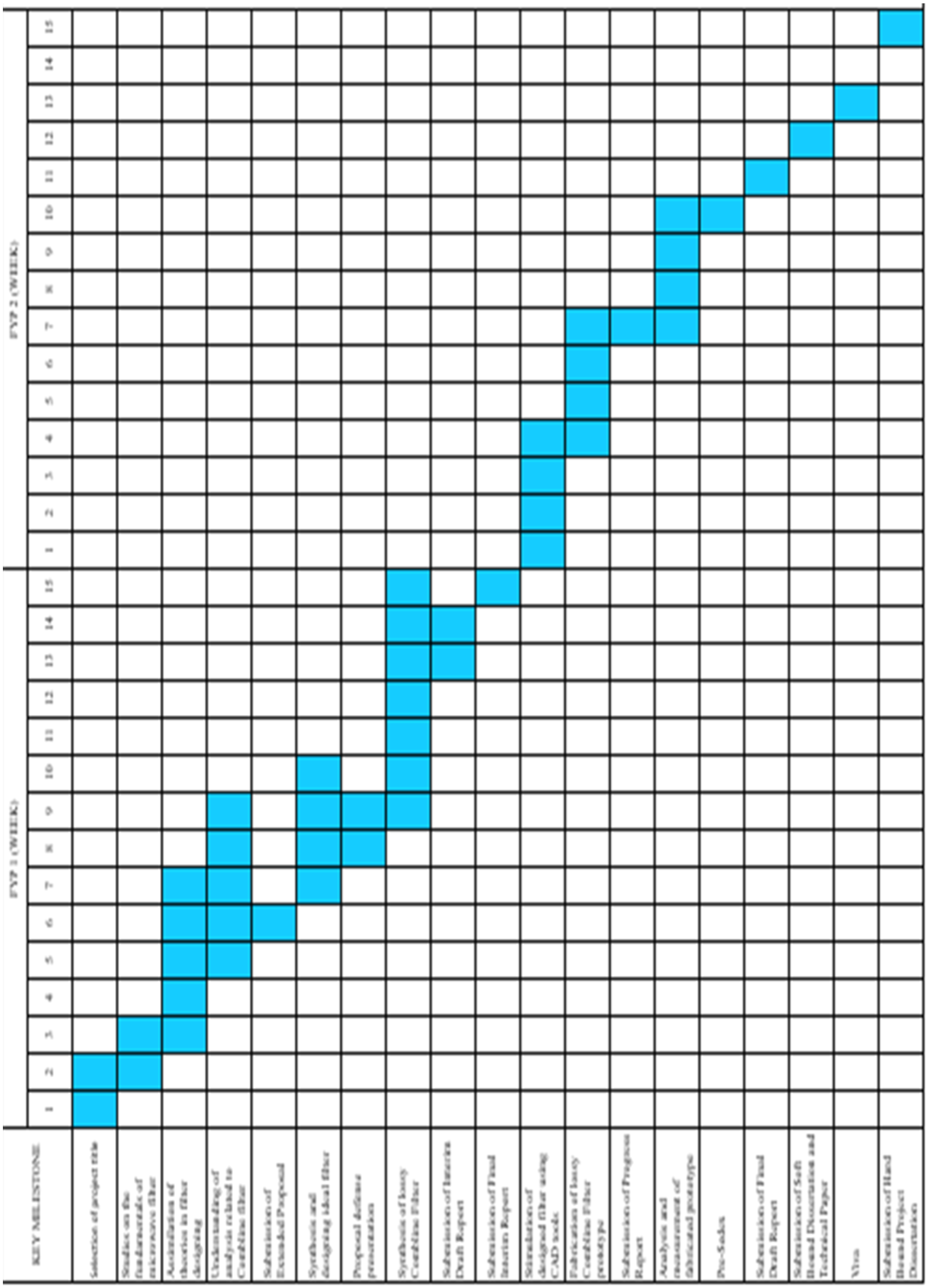
Phase 3: Project stimulation

- Computer-Aided Design (CAD) Tool software is used for stimulation purposes so that the filter response can be analyzed. Filters are designed based on the parameters from the previous calculations on the lossy combline filter.

Phase 4: Fabrication and measurement of the lossy combline filter

- Lossy combline filter designed is then sent for fabrication. The final model is then tested and measurements are collected. The data gathered is then compared to the theoretical calculations to verify the value difference.

3.3 Project Timeline (Gantt Chart)



CHAPTER 4

RESULTS AND DISCUSSIONS

A combline filter topology and its equivalent circuit is as follow:

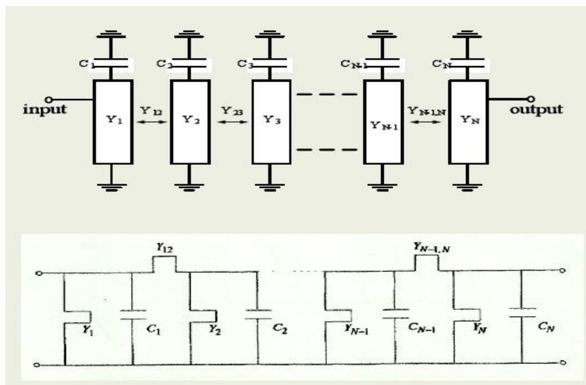


Figure 6: Combline filter and its equivalent circuit

The total loss, α_t in transmission line can be divided into two parts: conductor loss (α_c) and dielectric loss (α_d), where $\alpha_t = \alpha_c + \alpha_d$.

Conductor loss, α_c of stripline is derived and computed as follow:

$$a_c = \frac{0.0231\ R_s \varepsilon_r Z_o}{30\pi(b-t)}(A+B)$$

where

$$A = 1 + \frac{2W}{b-t} + \frac{1}{\pi}\frac{b+t}{b-t}\ln\left(\frac{2b-t}{t}\right)$$

and

$$B = \begin{cases} \dfrac{(0.35 - W/b)}{(b-t)(1+12t/b)^2}\left[\dfrac{t}{b}(17.45b + 35W) - 9W + 5.85 - 32.4t^2/b\right]\ ;\ Z_o\sqrt{\varepsilon_r}(1+2.3t/b) \geq 120 ohms \\ 0\ ;\ Z_o\sqrt{\varepsilon_r}(1+2.3t/b) < 120 ohms \end{cases}$$

Where R_S is the surface resistivity with formula

$$R_s = \sqrt{\frac{\omega\mu_0}{2\sigma}} \quad and \quad \mu_0 = 4\pi \times 10^7$$

Values of σ are dependent on the type of material used. Examples are as follow:

Aluminium	3.816×10^7
Gold	4.098×10^7
Silver	6.173×10^7

Dielectric loss, α_d of stripline is derived and computed as follow:

$$\alpha_d = \frac{k \tan\delta}{2}$$

$$where$$

$$k = \frac{2\pi f \sqrt{\varepsilon_r}}{c}$$

For a combline filter of degree 4, centered at frequency 2GHz with 40MHz bandwidth, the lowpass element values can be calculated with the following formula:

$$C_r = \frac{2}{\eta}\sin\left[\frac{(2r-1)\pi}{2N}\right]$$

$$K_{R,R+1} = \frac{\sqrt{\eta^2 + \sin(\frac{R\pi}{N})}}{\eta}$$

$$where\ \eta = \sinh\left[\frac{1}{N}\sinh^{-1}\left(\frac{1}{\varepsilon}\right)\right]$$

Using electrical length at ω_o, $\theta_o = 50^o$, α and β are obtained from the following formulas:

$$\alpha = \frac{2\omega_o \tan(\theta_o)}{\Delta\omega\{\tan(\theta_o) + \theta_o[1 + \tan^2(\theta_o)]\}}$$

$$\beta = \frac{1}{\omega_o \tan(\theta_o)}$$

Also, given $\beta = C/Y_{rr}$

Hence,

$$Y_{rr} = C\omega_0 \tan(\theta_0)$$

$$n_r = \left[\frac{\alpha C_{Lr} \tan(\theta_0)}{Y_{rr}}\right]^{1/2} \qquad (r = 1, \ldots, N)$$

$$Y_{r,r+1} = \frac{K_{r,r+1} \tan(\theta_0)}{n_r n_{r+1}} \qquad (r = 1, \ldots, N-1)$$

$$Y_r = Y_{rr} - Y_{r-1,r} - Y_{r,r+1} \qquad (r = 2, \ldots, N-1)$$

$$Y_1 = Y_N = Y_{11} - Y_{12} + \frac{1}{n_1^2} - \frac{1}{n_1 \cos(\theta_0)} \qquad (r = 1 \text{ and } N)$$

$$Y_0 = Y_{N+1} = 1 - \frac{1}{n_1 \cos(\theta_0)}$$

$$Y_{01} = Y_{N,N+1} = \frac{1}{n_1 \cos(\theta_0)}$$

The table below shows the tabulated result after being scaled to 50Ω impedance:

Table 2: Tabulated data after 50Ω impedance scaling

Element	Values
$Z_0 = Z_5$	66.295Ω
$Z_1 = Z_4$	66.33Ω
$Z_2 = Z_3$	52.34Ω
$Z_{01} = Z_{45}$	203.42Ω
$Z_{12} = Z_{34}$	1976.3Ω
Z_{23}	2577.3Ω
C	1.3356pF

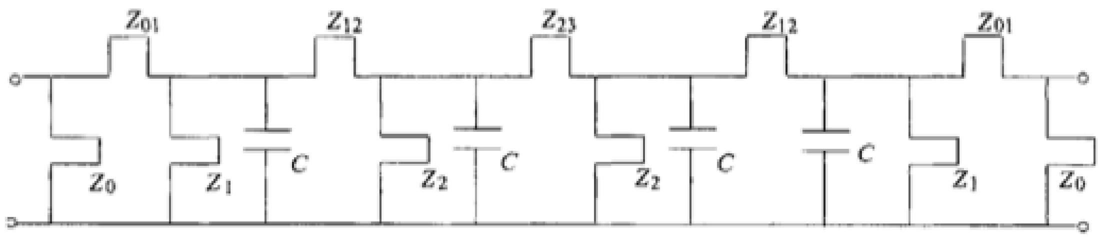


Figure 7: Equivalent circuit of a degree 4 combline filter

With the help of Advance Design System tool, the ideal transmission line schematic is designed and the response is observed. The response is then compared to the response generated by MATLAB coding as of in Appendix A. The following is the schematic layout and stimulated response for a combline filter of degree, N=4, centered at frequency 2GHz with 40MHz bandwidth. Length of resonators is 50º i.e. 20.83mm.

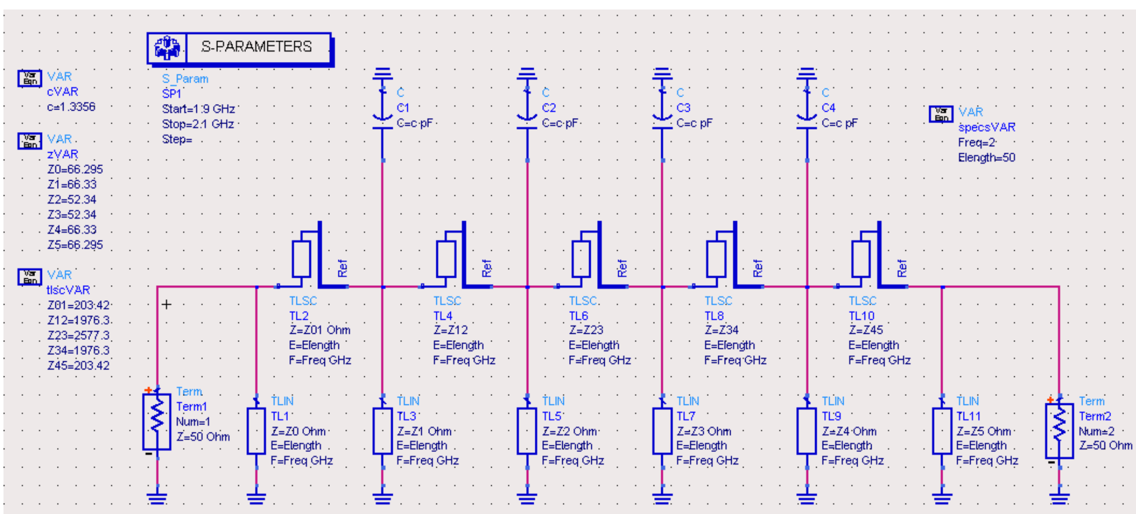


Figure 8: Schematic layout of combline filter using ideal transmission line

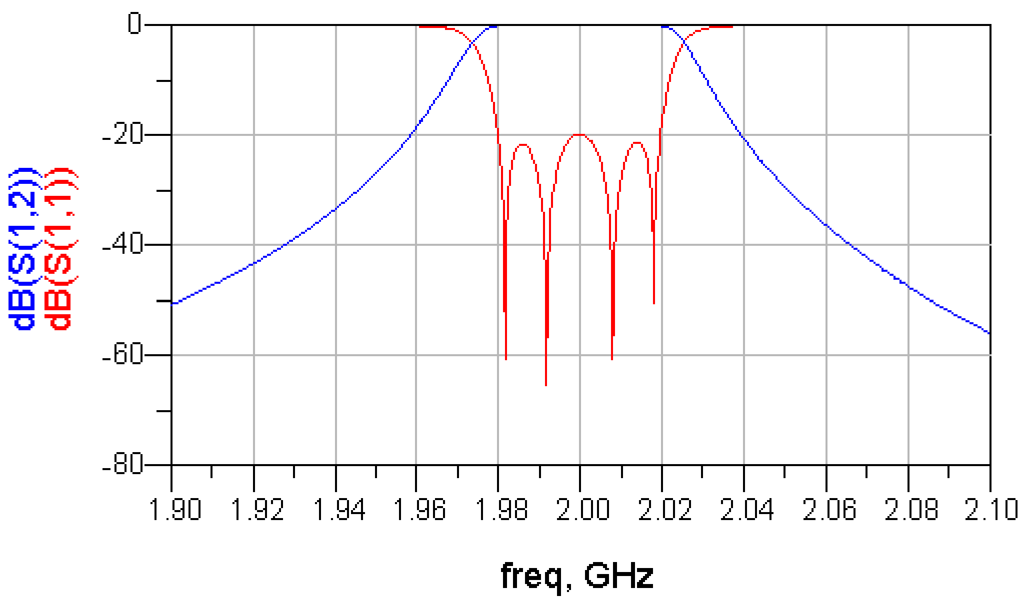


Figure 9: Ideal transmission line response of combline filter

Microwave office (AWR) is then used to design and generate the layout of a suspended stripline combline filter. Figure 12 and Figure 13 shows the schematic layout and response of suspended stripline combline filter designed respectively. The physical dimensions of the filter are calculated before the layout can be generated.

The static capacitance per unit length is obtained by the following formula:

$$\frac{C}{\varepsilon} = \frac{377}{Z_0(\varepsilon_r)^{1/2}}$$

The values obtained are tabulated in the following table:

Table 3: Tabulated values of static capacitance per unit length

Element	Values
$C_0/\varepsilon = C_5/\varepsilon$	3.8340
$C_1/\varepsilon = C_4/\varepsilon$	3.8320
$C_2/\varepsilon = C_3/\varepsilon$	4.8562

$C_{01}/\varepsilon = C_{45}/\varepsilon$	1.2495
$C_{12}/\varepsilon = C_{34}/\varepsilon$	0.1286
C_{23}/ε	0.0986

The fringing capacitances are obtained from the following:

Odd mode: $C_O = 2C_p + 2C_f' + 2C_{fo}' = C_e + 2\Delta C$

Even mode: $C_e = 2C_p + 2C_f' + 2C_{fe}'$

The coupling capacitance value is obtained as follow:

$$\Delta C = \frac{C_O - C_e}{2} = C_{fo}' - C_{fe}'$$

where C_p is the parallel plate capacitance between the metal strip and the ground, C_f' is the fringing capacitance of the isolated corners of the metal strip to the ground, C_{fe}' and C_{fo}' are the even-mode and odd-mode fringing capacitance of the coupled corners of the metal strip respectively.

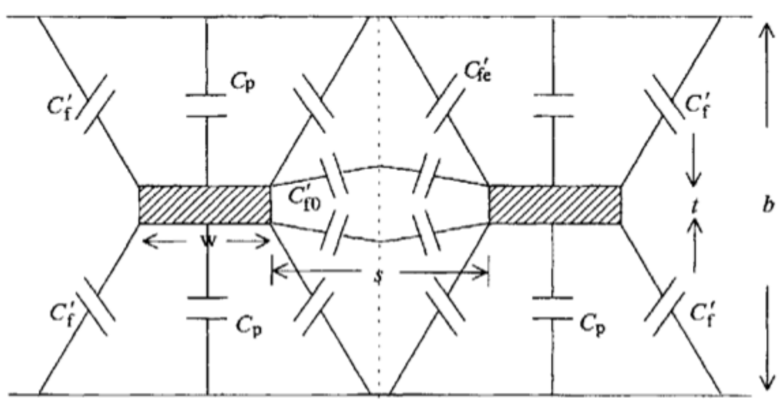


Figure 10: Coupled rectangular metal strips between parallel ground planes

With the values of fringing capacitance and coupling capacitance identified, the value of space gap between the metal strips can be obtained from the graph below:

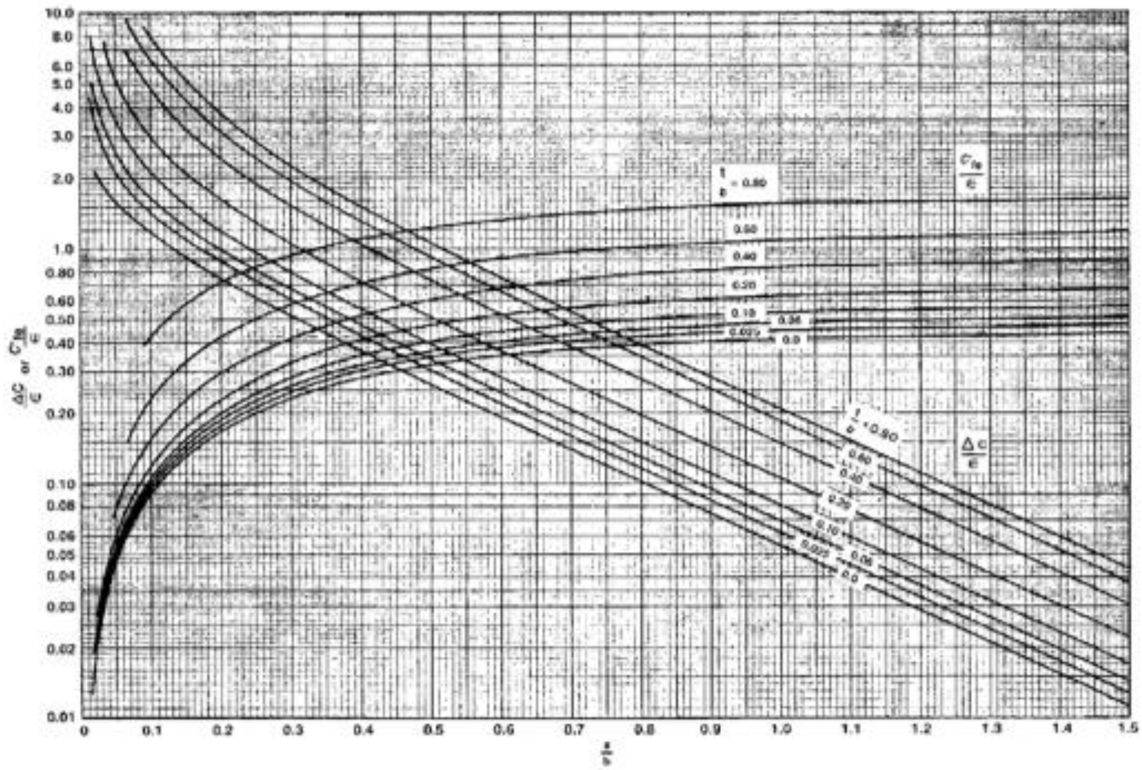


Figure 11: Even mode fringing capacitance and coupling capacitance as a function of s/b

The normalized width of the metal strip can be calculated from the following formula:

$$w_r = \frac{b-t}{4}\left(\frac{C_r}{\varepsilon} - 2C'_{\mathrm{fe}\ r-1,r} - 2C'_{\mathrm{fe}\ r,r+1}\right)$$

A maple coding has been written to ease the calculation of this process. The coding is displayed in Appendix B.

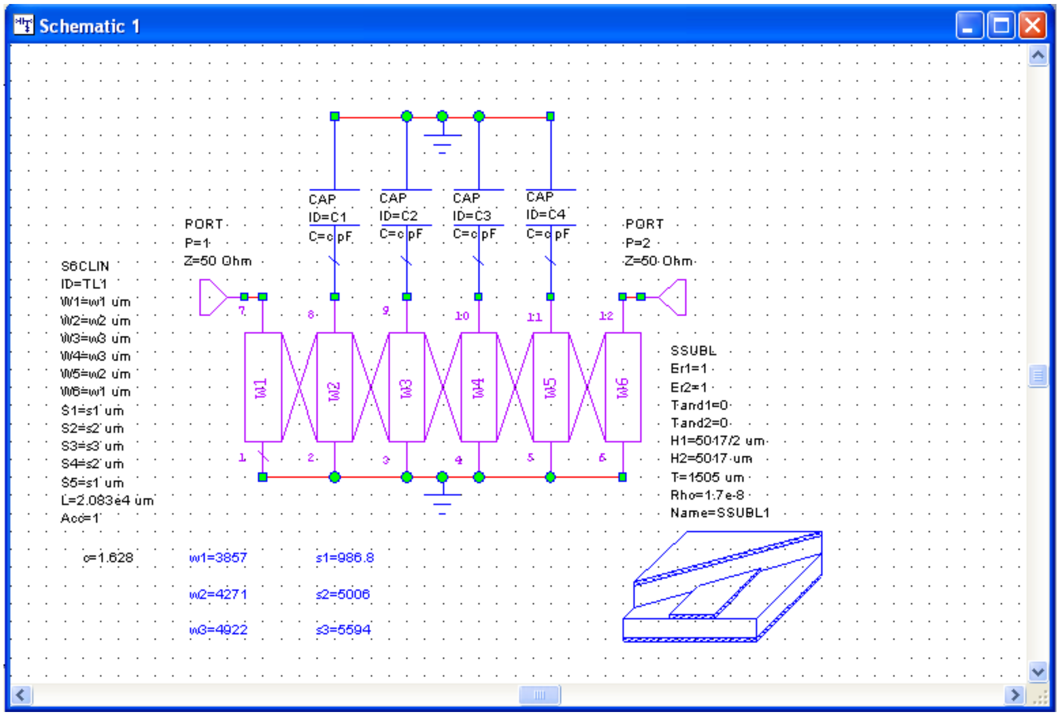


Figure 12: Schematic layout of a suspended stripline combline filter

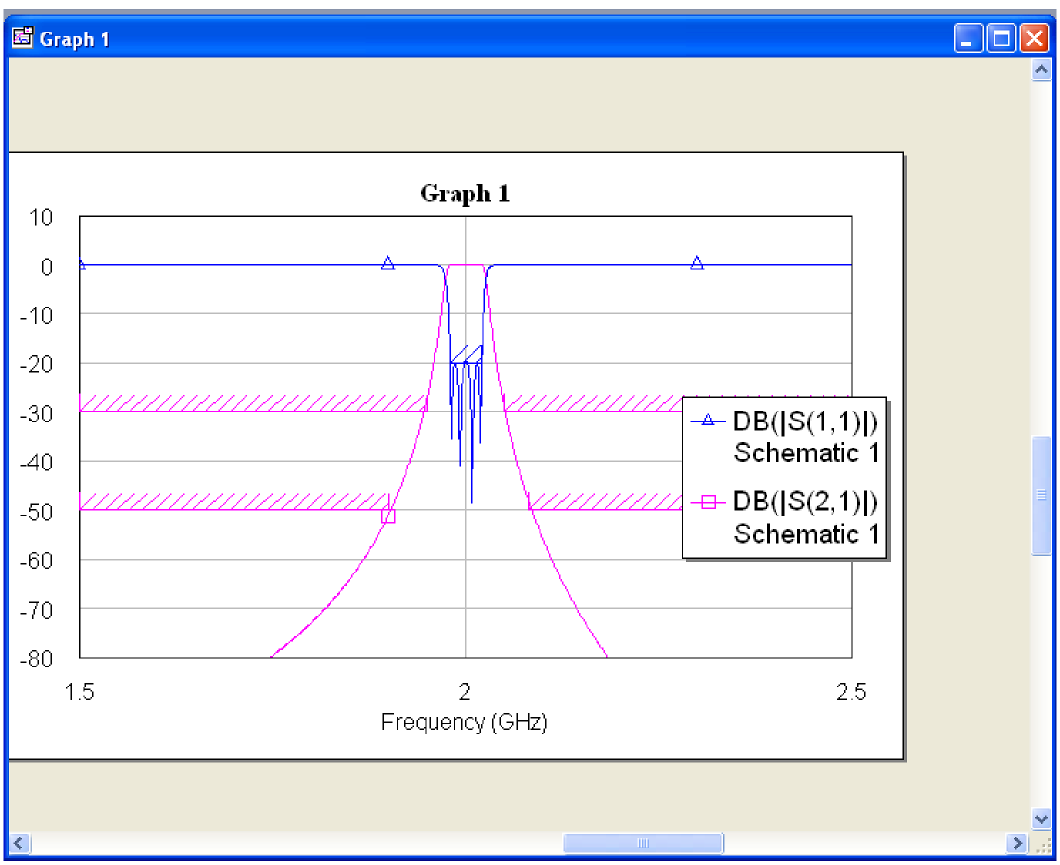


Figure 13: Suspended Stripline Combline filter response

CHAPTER 5
CONCLUSION AND RECOMMENDATION

A lossy combline prototype network was synthesized. Circuits were designed using appropriate CAD tools and fabrication of filter prototype is done. The objectives of this project are achieved.

With loss taken into consideration, the practical realization of filters is expected to have output values that are closer to the theoretical calculation computed. After the completion of this project, engineers will be able to come up with more accurate filter design parameters forecast with a smaller percentage error difference. With a more precise data, engineers are expected to be more efficient as time taken to tune and optimize results can be greatly reduced.

To ensure this project yields a more accurate output, it is recommended that a thorough research is done to identify all potential losses and a mindful yet detailed computation is carried out. Furthermore, a more in-depth exploration into CAD tools are encouraged to put these software into greater use.

REFERENCES

[1] Z. Zakaria, M.S. Jawad, N. Omar, A. R. Othman, and V. R. Gannapathy. (2013, Oct-Nov.). *Low-loss coaxial cavity microwave bandpass filter with post-manufacturing tuning capabilities*. [Online]. Available: http://www.enggjournals.com/ijet/docs/IJET13-05-05-032.pdf

[2] Jiafeng Zhou. (2010). *Microwave Filters, Microwave and Millimeter Wave Technologies from Photonic Bandgap Devices to Antenna and Applications*, [Online]. Available: http://www.intechopen.com/books/microwave-and-millimeter-wave-technologies-from-photonic-bandgap-%20devices-to-antenna-and-applications/microwave-filters

[3] I. Hunter, *Theory and Design of Microwave Filters*. London: The Institution of Engineering and Technology, 2001.

[4] J. S. Hong, and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications.* New York: Wiley, 2001.

[5] V. Miraftab, and M. Yu. (2008, Dec.). *Generalized Lossy Microwave Filter Coupling Matrix Synthesis and Design Using Mixed Technologies.* [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4682620&tag=1

[6] Anurag Bhargava. (2004, Jan.). *Combline Filter Design Simplified.* [Online]. Available: http://defenseelectronicsmag.com/site-files/defenseelectronicsmag.com/files/archive/rfdesign.com/mag/combline.pdf

[7] G. Matthaei, L. Young, and E.M.T. Jones, *Microwave Filters, Impedance Matching Networks and Coupling Structures*. Massachusetts: Artech House, 1964.

[8] M. Yu, W. C. Tang, A. Malarky, V. Dokas, R. Cameron, and Y. Wang. (2003,

Dec.). *Predistortion Technique for Cross-coupled Filters and its Application to Satelite Communication System.* [Online]. Available: http://maxwell.uwaterloo.ca/~myu/publications/03predist.pdf

[9] A. Guyette, I. Hunter, and R. Pollard. (2006, Nov.). *The Design of Microwave Bandpass Filters using Resonators with Nonuniform Q.* [Online]. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=01717760

[10] A. Guyette, I. Hunter, and R. Pollard. (2007, Jun.). *Exact Synthesis of Microwave Filters with Nonuniform Dissipation.* [Online]. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4263870

APPENDICES

APPENDIX A: MATLAB coding for synthesis of ideal combline filter

APPENDIX B: MAPLE coding for synthesis of suspended stripline

APPENDIX A: MATLAB CODING FOR SYNTHESIS OF IDEAL COMBLINE FILTER

```
clear all;
        close all;
        clc;

        % Center frequency of the combline filter
        fo  = input('Enter the center frequency fo [GHz]: ');
        % BWp = f2 - f1;
        BW = input('Enter the passband bandwidth [GHz]: ');
        LR  = input('Enter the Passband Return Loss [dB]:');
        % Order/Degree
        N  = input('Enter the order of the filter : ');
        % System Impedance
        Zo  = input('Enter the Characteristic Impedance (Zo) [Ohms]: ');

        %Center frequency in rad/s
        wo=2*pi*fo;
        %Passband bandwidth in rad/s
        deltaw=2*pi*BW;

        %Theta0 is chosen to be 50degree for optimum response with BW=cte
       % theta0=(50/180)*pi;              % i.e. 0.8726 radians approximately
             theta0=(45/180)*pi;       % for matched response
        %    Reflection Coefficient
        Ref = 10^(-LR/20);
        %    dB pass-band ripple
        Lar = -10*log10(1-Ref^2);
        % Ripple level epsillon
        epsillon = sqrt(10^(0.1*Lar) - 1);
        % Ref. Ian Hunter Page 126 to 129.
        eta = sinh((1/N)*asinh(1/epsillon));
        %Bandwidth scaling factor alpha and the constant beta. Ref. Ian Hunter Page
191.
        alpha = 2*wo*tan(theta0)/(deltaw*(tan(theta0)+theta0*(1+(tan(theta0))^2)));
        beta = 1/(wo*tan(theta0));
        %Tranformer Capacitor to match input/output to the resonator
        %By choosing Yrr = 1, C = beta*Yrr thus:
        Cb = beta;
        % Scaled value of C is Cb/Zo in nF
        Co = Cb/Zo;

        %Generating CLr values.
       for r=1:1:N
           CL(r) = (2/eta)*sin(((2.*r-1).*pi)./(2*N));
       end

       % Generating Kr,r+1 values
       for r=1:1:(N-1)
           K(r) = (sqrt(eta^2 + (sin((pi.*r)./N)).^2))./eta;
       end
      K(K==0)=[];

      % Yrr is chosen to be 1 early in the calculation of C.
      Yrr = 1;
      % nr values
      for r=1:1:N
          n(r)=((alpha*CL(r)*tan(theta0))./Yrr).^0.5;
      end

     % Yr,r+1 values
     for r=1:1:(N-1)
         Yrr1(r) = K(r)*tan(theta0)/(n(r)*n(r+1));
     end
```

```
%Yr values
for r=2:1:(N-1)
   Y1(r) = Yrr - Yrr1(r-1)-Yrr1(r);
end
% Y0, Y1, YN and YN+1 values
Y1(1) = Yrr - Yrr1(1) + (1/(n(1))^2) - 1/(n(1)*cos(theta0));
Y1(N) = Y1(1);
Y0 = 1 - 1/(n(1)*cos(theta0));
Y1(N+1) = Y0;
%Y01 and YN,N+1
Y01 = 1/(n(1)*cos(theta0));
YNN1 = Y01;

%Putting all Yr elements together in one matrix (Admittance)
%Getting the corresponding scaled impedance
for r=1:1:(N+2)
    if r==1
        Y(r) = Y0;
        Zodd(r) = Zo*(1/Y(r));
    elseif r>1
        Y(r) = Y1(r-1);
        Zodd(r) = Zo*(1/Y(r));
    else
    end
end

  %Putting all Yr,r+1 elements together in one matrix (Admittance)
  %Getting the corresponding scaled impedance
for r=1:1:(N+1)
    if r==1
        Yr(r) = Y01;
        Zeven(r) = Zo*(1/Yr(r));
    elseif (r>1) && (r<=N)
        Yr(r) = Yrr1(r-1);
        Zeven(r) = Zo*(1/Yr(r));
    elseif r==(N+1)
        Yr(r) = YNN1;
        Zeven(r) = Zo*(1/Yr(r));
    else
    end
end

 f = 0:0.001:30;                  % Range of the frequency in GHz
 w = 0:(2*pi*0.001):(2*pi*30);    % Range of w = 2*pi*f.
 M = 2*N+3;

 for i=1:1:30001
  for t=1:1:M
      if t==1
         % Electrical length
         theta = theta0*(w(i)./wo);
         % Impedance for Z1
         Z(1) = -j./(Zodd(1)*tan(theta));
         % T Matrix
         T = [1 0;Z(1) 1];
      elseif (t>1) && (t<M)
             k=mod(t,2);
         if k==0
             % Electrical length
             theta = theta0*(w(i)./wo);
             u = t/2;
             Z(t) = j.*Zeven(u)*tan(theta);
             % T Matrix
             Tnew = T*[1 Z(t);0 1];
             T = Tnew;
         elseif k==1
             % Electrical length
             theta = theta0*(w(i)./wo);
             v = round(t/2);
             Z(t) = j.*w(i).*Co - j./(Zodd(v)*tan(theta));
             % T matrix
             Tnew = T*[1 0; Z(t) 1];
             T = Tnew;
         else
         end
      elseif t==M
             % Electrical length
```

```
                %theta = theta0*(w(i)./wo);
                v = round(t/2);
                Z(t) = -j./(Zodd(v)*tan(theta));
                % T matrix
                Tnew = T*[1 0; Z(t) 1];
                T = Tnew;
            else
            end

        end

    T;

% Getting ABCD values by identification using 2X2 Matrix T=[A B;C D] by using
    A = T(1,1);
    B = T(1,2);
    C = T(2,1);
    D = T(2,2);

 % Computing S12 values for different values ABCD resulting from the
 % variation in w.
    Sa(i) = abs(2./(A+(B./Zo)+(C.*Zo)+D));
    Sb(i) = abs(1 - (abs((2./(A+(B./Zo)+(C.*Zo)+D)))).^2);
      end

      Zodd
      Zeven
%                                                      4
% Plotting with A,B,C,D parameters, |S12|^2 = -------------------
%                                              |A+(B/Zo)+(C*Zo)+D|^2

    S12 = 20*log10(Sa);  % Computing the dB values of |S12|^2
    S11 = 10*log10(Sb);

    plot(f,S12,'blue', f,S11,'red')
    graph = plot(f,S12,'blue', f,S11,'red');
    % Setting the line width or thickness for both curves
    set (graph, 'LineWidth',1.5);
    title('Response for Chebyshev Combline Filter');
    ylabel('|S12|^2 and |S11|^2 in dB');
    xlabel('f in GHz');
    axis([0 (2*fo) -80 5]);
    grid on;
    % Inserting legend for the plot
    legend('S12','S11');
    % Moving the legend to the lower right corner of the graph
    legend('location','SouthEast');
```

APPENDIX B: MAPLE CODING FOR SYNTHESIS OF SUSPENDED STRIPLINE COMBLINE FILTER

```
> restart
################################################## This
    programme code contains 3 parts.

    ## Part I : User's Specification

    ## Part 2: Calculation of Impedance of rectangular bars and
    coupling gaps

    ## Part 3: Calculation of the Physical dimension of rectangular
    bars and coupling gap of two adjacent bars

    ###############   Step 1    User Specification
    ##############################

f0 := 2 ## Center frequency of the combline filter [GHz]   User
    's input 1
                                        2
BW := 0.04 ##Passband bandwidth [GHz]  User's input 2
                                        0.04
fs := 2.5 # Stopband frequency [GHz]  User's input 3
                                        2.5
LA := 80 # Stopband Insertion Loss [dB]  User's input 4
                                        80
LR := 20 ## Passband Return Loss [dB]  User's input 5
                                        20
Z0 := 50 ## Characteristic Impedance (Zo) [Ohms]  User's input 6
                                        50
αp := 1.2 #`#`Passband Attenuation  User's input 7
                                        1.2
tb := 0.3 # ratio of width to height  User's input 8
                                        0.3
if 0 < tb < 0.5 then print(Condition satisfied)
    else print(Condition doesn't meet) end if;
                               Condition satisfied
################################################   Step 1    U
    Specification                ##############################
-

################################################    Step 2
    Calculation of Impedance of rectangular bars
    ##############################
```

$$S := \frac{2(fs - f0)}{BW}$$ # ratio of Stopband to Passband bandwidth

25.0000000(

> $N1 := evalf\left(\frac{LA + LR + 6}{20\log_{10}\left(S + \sqrt{S^2 - 1}\right)}\right)$

3.11985631'

$N := \text{ceil}(N1)$

N is the order of the filter. Ceil(x) is the smallest integer greater than or equal to x, Eg ceil(2.5)=3 means that 3 is the smallest integer greater (or equal) to 2.5

4

$deltaw := evalf(2\,\pi\,BW)$ *## Passband bandwidth in rad/s*

0.251327412:

$w0 := evalf(2\,\pi\,f0)$ *## Center frequency in rad/s*

12.5663706:

$theta0 := evalf\left(\frac{50\,\pi}{180}\right)$

theta0 is chosen to be 50degree for optimum response with BW

0.872664626:

$l := \frac{50 \cdot 3e8}{360\,f0 \cdot 1e9}$ *## physical length in meter*

0.0208333333·

$Ref := evalf\left(10^{-\frac{LR}{20}}\right)$

theta0 is chosen to be 50degree for optimum response with BW

0.100000000(

$Lar := -10\log_{10}\left(1 - Ref^2\right)$ *## dB pass-band ripple*

0.0436480540:

$\varepsilon := \sqrt{10^{0.1\,Lar} - 1}$ *## Ripple level epsillon*

0.100503781(

$\eta := \sinh\left(\frac{1}{N}\,\text{arcsinh}\left(\frac{1}{\varepsilon}\right)\right)$

0.820124345:

$\alpha := \frac{2\,w0\,\tan(theta0)}{deltaw\,\left(\tan(theta0) + theta0\,\left(1 + \tan(theta0)^2\right)\right)}$

Bandwidth scaling factor alpha and the constant beta

36.0717338:

> $\beta := \frac{1}{w0\,\tan(theta0)}$

Bandwidth scaling factor alpha and the constant beta

0.0667734269'

$Cb := \beta$

0.0667734269'

$Co := \frac{Cb}{Z0} \cdot 10^{-9}$ *## Scaled value of C is Cb/Zo in F*

$1.335468539\,10^{-12}$

$lC := evalf\left(\frac{Co}{\frac{8.854 \cdot 10^{-12} \cdot 2\,\pi}{\ln(1.25)}}\right)$ *## depth of the screw*

0.00535671592

for r **from** 1 **to** N **do** $CL_r := evalf\left(\frac{2}{\eta}\,\sin\left(\frac{(2\,r - 1)\pi}{2\,N}\right)\right)$ **end do**

0.933232709.
2.25302306.
2.25302306.
0.933232709.

$$Q := \frac{4.343\, f0}{BW\, \alpha p} \sum_{i=1}^{N} CL_i$$ *## Quality factor*

1153.15906

$$\textbf{for } r \textbf{ from } 1 \textbf{ to } N-1 \textbf{ do } K_{r,r+1} := evalf\left(\frac{\sqrt{\eta^2 + \sin\left(\frac{\pi r}{N}\right)^2}}{\eta}\right) \textbf{ end do}$$

1.32037098
1.57694611
1.32037098

$$Yrr := 1$$

1

$$\textbf{for } r \textbf{ from } 1 \textbf{ to } N \textbf{ do } n_r := \sqrt{\frac{\alpha\, CL_r \tan(theta0)}{Yrr}} \textbf{ end do}$$

6.33390754
9.84146069
9.84146069
6.33390754

$$> \textbf{ for } r \textbf{ from } 1 \textbf{ to } N-1 \textbf{ do } Y_{r,r+1} := \frac{K_{r,r+1} \tan(theta0)}{n_r\, n_{r+1}} \textbf{ end do}$$

0.0252435923
0.0194036842
0.0252435923

$$\textbf{for } r \textbf{ from } 2 \textbf{ to } N-1 \textbf{ do } Y_r := Yrr - Y_{r-1,r} - Y_{r,r+1} \textbf{ end do}$$

0.955352723.
0.955352723.

$$Y_1 := Yrr - Y_{1,2} + \frac{1}{n_1^2} - \frac{1}{n_1 \cos(theta0)}$$

0.754064300

$$Y_N := Y_1$$

0.754064300

$$Y_0 := 1 - \frac{1}{n_1 \cos(theta0)}$$

0.754381664

$$Y_{N+1} := Y_0$$

0.754381664

$$Y_{0,1} := \frac{1}{n_1 \cos(theta0)}$$

0.245618335.

$$Y_{N,N+1} := Y_{0,1}$$

0.245618335.

$$\textbf{for } r \textbf{ from } 0 \textbf{ to } N+1 \textbf{ do } Z_r := \frac{Z0}{Y_r}; \textbf{ end do}$$

Impedance of rectangular bars [Ohm]

66.2794475
66.3073427
52.3366907
52.3366907

66.3073427:
66.2794475‹

for i **from** 0 **to** $N+1$ **do**; **for** j **from** 0 **to** $N+1$ **do if** $j-i=1$ **then** $Z_{i,j} := \dfrac{Z0}{Y_{i,j}}$; $print(i, j, Z_{i,j})$; **end if end do end do**

0, 1, 203.567864:
1, 2, 1980.70065‘
2, 3, 2576.83022
3, 4, 1980.70065‘
4, 5, 203.567864:

Step 2 Calculation of Impedance of rectangular bars

–
–

############################### Step 3 Calculation of the Physical dimension of rectangular bars and gap of two adjacent bars ##############################

> $b := evalf\left(\dfrac{Q}{(2000 - 7.5\, Z0)\sqrt{f0}}\right)$ # height of substrate in cm

0.0252435923‘
0.0194036842‹
0.0252435923‘

for r **from** 2 **to** $N-1$ **do** $Y_r := Yrr - Y_{r-1,r} - Y_{r,r+1}$ **end do**

0.955352723:
0.955352723:

$$Y_1 := Yrr - Y_{1,2} + \frac{1}{n_1^2} - \frac{1}{n_1 \cos(theta0)}$$

0.754064300

$$Y_N := Y_1$$

0.754064300

$$Y_0 := 1 - \frac{1}{n_1 \cos(theta0)}$$

0.754381664‘

$$Y_{N+1} := Y_0$$

0.754381664‘

$$Y_{0,1} := \frac{1}{n_1 \cos(theta0)}$$

0.245618335:

$$Y_{N,N+1} := Y_{0,1}$$

0.245618335:

for r **from** 0 **to** $N+1$ **do** $Z_r := \dfrac{Z0}{Y_r}$; **end do**

Impedance of rectangular bars [Ohm]

66.2794475‹
66.3073427:
52.3366907
52.3366907
66.3073427:
66.2794475‹

for i **from** 0 **to** $N+1$ **do**; **for** j **from** 0 **to** $N+1$ **do if** $j-i=1$ **then** $Z_{i,j} := \frac{Z0}{Y_{i,j}}$; $print(i, j, Z_{i,j})$; **end if end do end do**

0, 1, 203.567864:
1, 2, 1980.70065'
2, 3, 2576.83022
3, 4, 1980.70065'
4, 5, 203.567864:

Step 2 Calculation of Impedance of rectangular bars

\-
\-

################################ Step 3 Calculation of the Physical dimension of rectangular bars and gap of two adjacent bars ################################

> $b := evalf\left(\frac{Q}{(2000 - 7.5\, Z0)\sqrt{f0}}\right)$ *# height of substrate in cm*

> $c1 := evalf\left(\frac{1}{\sqrt{1 - e^{-\pi\, dC}}}\right)$

564.188924(

$$s_0 := evalf\left(\frac{2(b-t)}{\pi}\sqrt{c1^2 - 1}\; int\left(\frac{1}{1+x^2}\sqrt{\frac{x^2}{c1^2 + x^2}}, x = 0 ..10\right)\right)$$

0.00515985253

$$sb0 := \frac{\operatorname{Re}(s_0)}{b}$$

1.02829194(

$$G0 := int\left(1 + \mathrm{I}\sqrt{c1^2 - 1}\sqrt{\frac{\left(1 - e^{-\pi z}\right)^2}{\left(1 - e^{-\pi z}\right)^2 - c1^2\left(1 + e^{-\pi z}\right)^2}}, z = 0 ..10, \text{numeric} = \text{true}\right)$$

0.441271700

$$Cf := -dC + \operatorname{Re}(G0)$$

0.441270700

$w_0 := \frac{b-t}{4}\left(C_0 - 2\, Cf - 2\, Cfe_{0,1}\right)$ *# width of the first bar*

0.00416049010

> $w_{N+1} := w_0$: *# width of the last bar*