Theoretical and CAD Modelling of Distributed Filter Design with Finite Q Resonators

by

Lee Huey Jiun
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Universiti Teknologi Petronas
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved:

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Dr. Wong Peng Wen
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

January 2015

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.

LEE HUEY JIUN

ABSTRACT

This project focuses on theoretical modelling of a lossy combline filter in MATLAB. Classical designs of filters have not been taking into consideration of various loss factors related to the resonator in MATLAB. With that, there will always be inconsistency to the simulated response due to the response gap between ideal and lossy. Hence, modelling of a lossy combline filter will significantly improve the traditional way of filter designs by incorporating conductor and dielectric losses in practical realization. Simulations of both ideal and lossy combline filter will be performed using MATLAB, Maple and Advanced Design System (ADS) as well as for comparison and analysis purposes.

ACKNOWLEDGEMENT

First, I would like to express my gratitude to my supervisor, Dr Wong Peng Wen for his guidance and support throughout the two semesters of my final year project. He has been kind and willing to spend his precious time in guiding me whenever I face difficulties in the process of modelling in MATLAB despite of his packed work schedule.

Not only that, I also owe my deepest gratitude to Mr. Sovuthy Cheab, a postgraduate student of Dr. Wong. He was selfless and willing to spend his time despite his busy workload to guide me along by enlightening me on the theory of microwave filters and also on the designing using ADS as all those were totally new to me. His unfailing support, encouragement and advices to me throughout the final year project has truly play a big role of me progressing in the project. Not forgetting the rest in the team, Mr. Chew Xiao Yan and Mr. Soheatra Seoung for their willingness and generosity in sharing their knowledge no matter in microwave filters or in MATLAB. All of those have truly help in allowing me to learn and complete the project. It has really been an honor to be able to get to know and learn from them.

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LIST OF ABBREVIATIONS

CAD	–	Computer Aided Design
MATLAB	–	Matrix Laboratory
ADS	–	Advance Design System
MHz	–	Megahertz
GHz	–	Gigahertz
TEM	–	Transverse Electromagnetic
SSSL	–	Suspended Substrate Stripline
CST	–	Computer Simulation Technology
HFSS	–	High Frequency Structural Simulator

CHAPTER 1

INTRODUCTION

1.1. Background

Microwave filters, one of the types of electronic filters, are designed to work on signals which fall into the medium frequency and extremely high frequency range, from range of megahertz (MHz) to gigahertz (GHz). The applications for these ranges are usually of wireless communications, television and radio broadcast and more. In communication systems, filters are useful in removing unwanted components from certain signals, for example noise which contributes to loss of the system's performance [1]. Various types and designs of filter responses have been taken into considerations for different types of situations in incorporating losses and inconsistency of stimulated response performance. The types of filters which are commonly available are low-pass filters, high-pass filters, band-pass filters and band-stop filters.

Based on the desired type and design of filter response, it can be built using different type of technologies. The components and mathematical properties of those technologies might be identical, however they will each have physical properties which can be differentiated. With the demand of increasing applications on higher frequency ranges with better performances in a compact structure, distributed filters have been increasingly gaining fame for its ability to overcome issues of insertion loss, operation frequency and linear power handling in which classical lumped element filters are unable to excel in those areas.

Among the distributed filters, combline filter topology has been chosen due to its advantages over the other types of filters such as interdigital filters. Through combline filter topology, high "Q" factors are able to be achieved and the designs of the filters are claimed to be easy with compact structures. Combline filters also possess high selectivity features and able to provide steep cutoff on the higher side of passband.

In this research, the modelling via theory and Computer Aided Design (CAD) of distributed combline band-pass filter using finite Q resonators is proposed to perform necessary modelling associated to various medium of transmission and properties to take into consideration of the loss factor in the design stage.

1.2. Problem Statement

Taking the classical techniques of synthesizing filters, basic low-pass prototype networks with the lossless passive resonators can be produced. The modelling of the system has always been assumed to be lossless. However, the real elements used in the classical method of synthesis will include resistive loss associated with the inductor in the designs in which the situation where the existence of response gap will always be in between. Deterioration of filter's performance is also prone to occur due to the finite unloaded Q factor. This shows that classical design of distributed filters (combline filters) does not take into consideration of the loss factor related to the resonator especially in MATLAB. Without taking into consideration of the loss factor at the beginning of designing, the design will eventually ends up to have inconsistency of performance in contrast to the simulated response. This situation will lead to unreliable performance of the system.

1.3. Objectives and Scopes of Study

This research is aimed to significantly develop and compare filters realized in various transmission lines to the simulated response in order to reduce the response gap.

The objectives of this research are:

1. To develop and compare a lossy combline filter topology

2. To perform theoretical and CAD modelling on distributed combline filter design with finite Q resonators
3. To incorporate the loss factor into the combline filter in the design process
4. To validate results using schematic circuit design (ADS)
5. To classify most commonly used transmission lines

The scopes of the study to assist in achieving the objectives of this research within the given time frame are:

1. Fundamentals of microwave filter designing
2. Distributed combline filter design with finite Q resonators
3. Modelling using CAD tools
4. Simulation and comparison of lossy combline filter designed

This project mainly involves design in communication and microwave and through research and understanding of the fundamentals of its theory, it will be helpful in modelling process.

1.4. Relevancy and Feasibility

This research is much relevant to the studies of Electrical and Electronic Engineering as it involves the research of microwave filters and programming in MATLAB. It is fully feasible with the presence of MATLAB software and other CAD tools.

CHAPTER 2

LITERATURE REVIEW

2.1 Microwaves

Electromagnetic waves are invisible electric force field composed of charged particles such as electrons and protons [2]. The act of oscillating magnetic fields together with electric fields will produce electromagnetic waves. Through electromagnetic waves, transmission of energy can be done without any medium or through vacuum. Among the series of electromagnetic waves, microwaves plays an important role especially in the field of communication systems. Microwaves are electromagnetic waves within the frequency range of 300 MHz and 300 GHz and of length ranging from one millimeter to one meter [3].

2.2 Types of Filters

Filter is essential in the design of microwave device where it can be used in controlling the pass and stopband of the designed filter to achieve the desired response waveforms by having minimum attenuation and proper transmission zeros. The synthesizing and analysis are usually done in frequency domain. Hence, the frequency response of filters can be categorized into low-pass filter, high-pass filter, band-pass filter and band-stop filter as shown in Figure 2.1 [4]. Each of them has their own characteristics in describing the frequency bands it rejects and allows. Most filter designs will progress from building a low-pass filter and slowly transform or combine two types of responses into a band-pass or band-stop filter. An ideal filter shall possesses the following characteristics: zero insertion loss, constant group delay over the desired passband and infinite rejection at anywhere else.

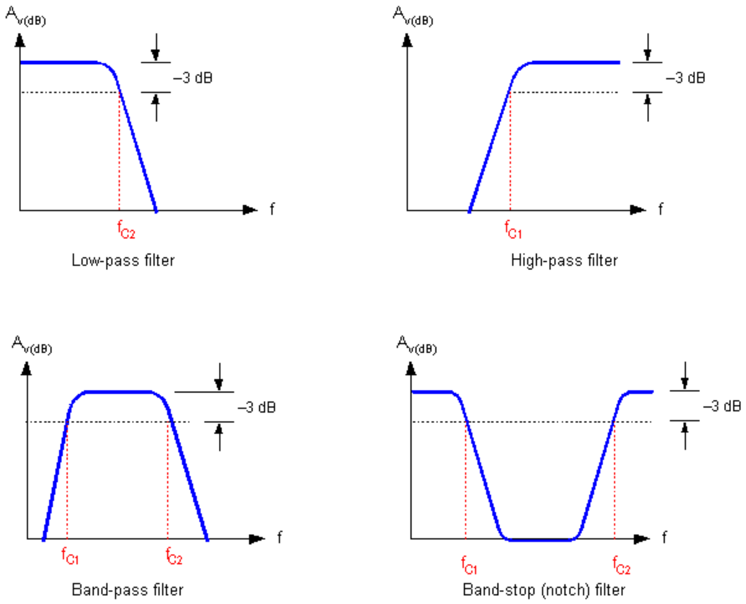

FIGURE 2.1. Frequency Response Curves of Filters

2.3 Q-Factor

Q, the quality factor describing the reactive components (capacitors and inductors) in an active filter, is a measurement of the ratio of energy stored versus energy loss in per unit time [5]. It is also equivalent to the division of center frequency over the bandwith ($\frac{\omega_0}{BW}$). The center frequency which is also known as the resonant frequency can be obtained when the electric stored energy is cancelled with magnetic stored energy, allowing dissipation of real power only. A higher value of Q is desired as it will contribute to the higher degree of similarity with the ideal frequency response, less attenuation and less insertion loss as well. The higher the value of Q, the stronger the resonance of the filter circuit.

$$Q = \omega \frac{\text{energy stored}}{\text{average power dissipated}} \tag{2.1}$$

2.4 Analysis using ABCD and S-Parameters

Among the techniques in designing a microwave filter, one of the most important characterization techniques used consists of scattering parameters (S-parameters) and also the ABCD parameters. These two parameters are often used in linking the two-port systems and both are closely related to each other.

S-parameters[6] provides relations between input and output incident waves and input and output reflected waves with the connection to a source resistance and a load resistance.

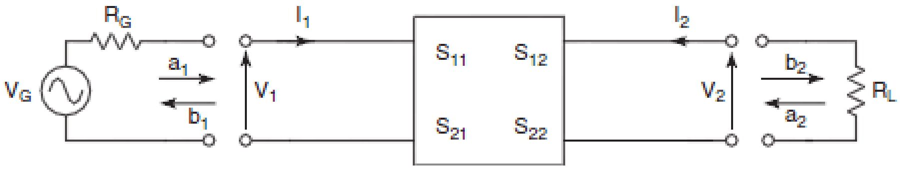

FIGURE 2.2. Notations of Scattering Matrix of A Two-Port System

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} \qquad S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0} \qquad S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} \qquad S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0} \qquad (2.2 – 2.5)$$

S_{11} is the input reflection coefficient, S_{21} is the output reflection coefficient, S_{12} is the reverse gain and S_{21} is the forward gain.

The ABCD parameters have an upper hand when it comes to designing microwave filters as simulations including all the cascaded lumped elements such as inductors, capacitors and transformers. Besides, ABCD parameters can always be converted to S-parameters and vice versa. In times, there are possibilities where model of combination of lumped elements are required rather than directly perform interpretation on S parameters.

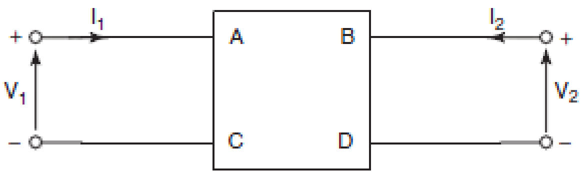

FIGURE 2.3. Notations of ABCD Matrix of A Two-Port System

$$A = \left.\frac{V_1}{V_2}\right|_{I_2=0} \qquad B = \left.\frac{V_1}{I_2}\right|_{V_2=0} \qquad C = \left.\frac{I_1}{V_2}\right|_{I_2=0} \qquad D = \left.\frac{I_1}{I_2}\right|_{V_2=0} \qquad (2.6 – 2.9)$$

A is the forward voltage gain, B is the forward transfer impedance, C is the forward transfer admittance and D is the forward current gain.

2.5 Types of Transmission Lines

There are various types of transmission modes for transverse electromagnetic (TEM) as shown in Figure 2.4. TEM is the transmission where both electric and magnetic field are at 90° to each other, and at the same time orthogonal with the direction of propagation too.

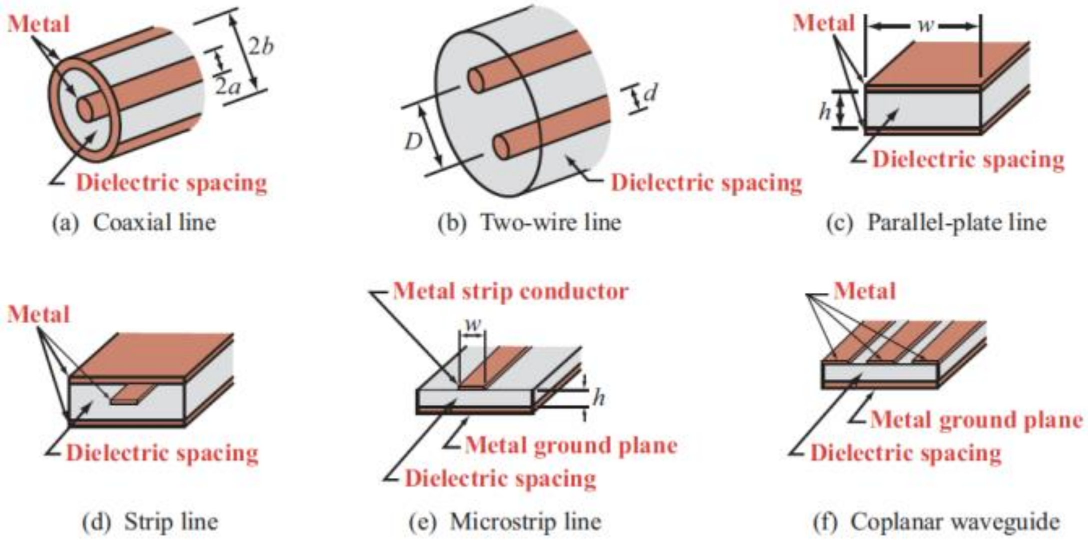

FIGURE 2.4. Types of TEM Transmission Modes

2.5.1 Coaxial Line

Coaxial transmission line is one of the types to be realized using combline filters. The coaxial transmission is able to provide desirable TEM mode of transmission. It consists of two conductors, the inner and outer conductor. Both are being separated by a continuous solid dielectric insulator. As shown in Figure 2.5, a represents the inner conductor whereby b represents the outer conductor. These parameters will be useful in further calculations.

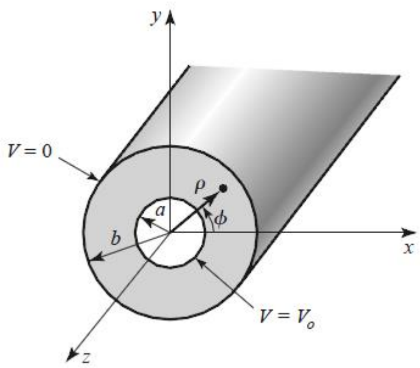

FIGURE 2.5. Geometry of Coaxial Line [7]

2.5.2 Microstrip Line

Microstrip is the most common type of transmission line, suitable for both hybrids and monolithic circuits. It is moderately dispersive at high frequencies and can be fabricated by photolithographic processes. Microstrip line is easily miniaturized and has the ability to integrate both active and passive microwave devices. As shown in Figure 2.6 [7], microstrip line consists of a conductor with width, *W* printed on a thin and grounded dielectric substrate with the thickness of *d* and its relative permittivity of ϵ_r.

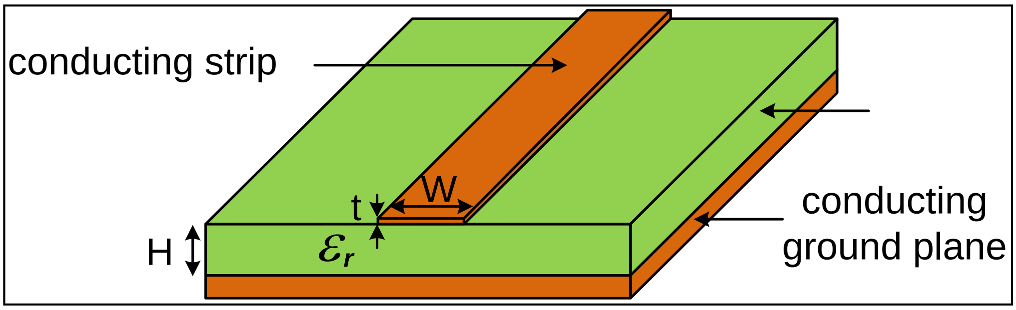

FIGURE 2.6. Geometry of Microstrip Line

2.5.3 Strip Line

Stripline is planar type of transmission line and it is best to be used with passive components. From Figure 2.7, the geometry of stripline can be explained as placing a thin conducting strip of width *W* in the center of two wide conducting ground planes. Both the ground planes are being separated with parameter *b*, and the region in between is filled with dielectric material which may have different value of dielectric constants. Air dielectric is being used occasionally in order to minimize the loss [7].

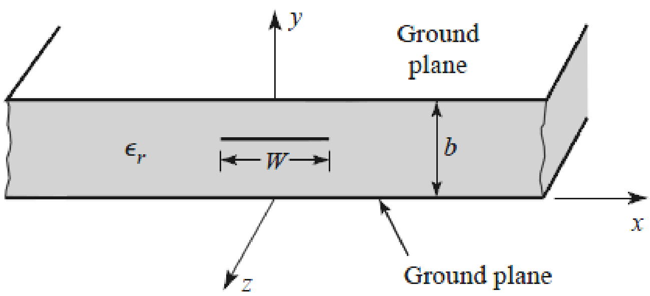

FIGURE 2.7. Geometry of Strip Line

2.5.4 Suspended Substrate Stripline (SSSL)

Suspended substrate stripline has many of the properties of stripline in which it makes SSSL very similar to stripline, however it is much easier to be fabricated in many types of circuits with either hard or soft substrate compared to stripline. It possesses low effective dielectric constant due to the non-homogeneous dielectric and hence induces less loss.

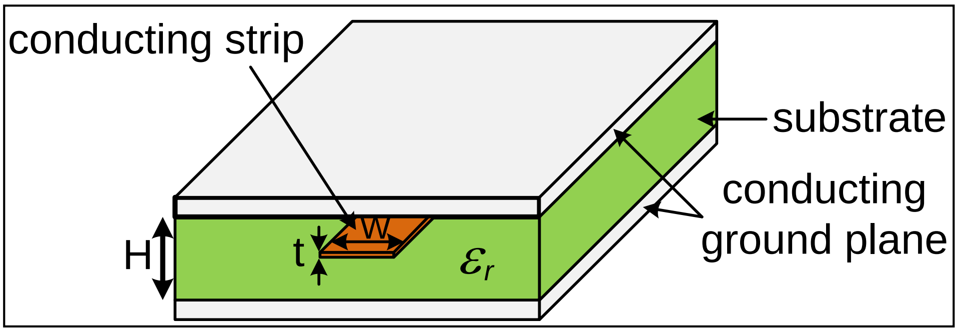

FIGURE 2.8. Geometry of Suspended Substrate Stripline

2.6 Combline Filters

The basic approach in designing a microwave filter has traditionally been by using the lumped element microwave filter. However, most of the designs are based on lossless lumped element microwave filter in which is not possible to be realized physically in real-life situations [8]. Thus, lumped element method has not been convincing for limitation of Q factor in high frequency range as well [9]. In conjunction to that, Matthaei has been the first to recommend one of the distributed element filter as replacement for better practical realization in year 1964 [10]. Compared to lumped element filter, distributed filter is able to show better response with less loss, better power handling and at the same time provide the positive usability to operate at higher frequencies. Among the choices of distributed filters, combline filter emerged to be a good choice with the following positive characteristics [9]:

- reliable stopbands
- manipulative steepness of cutoff rate for the high side of passband
- compact in structure
- high selectivity features
- adequate coupling
- production tolerance friendly (maintainable adequate coupling for resonators)
- able to be eliminate dielectric loss during fabrication

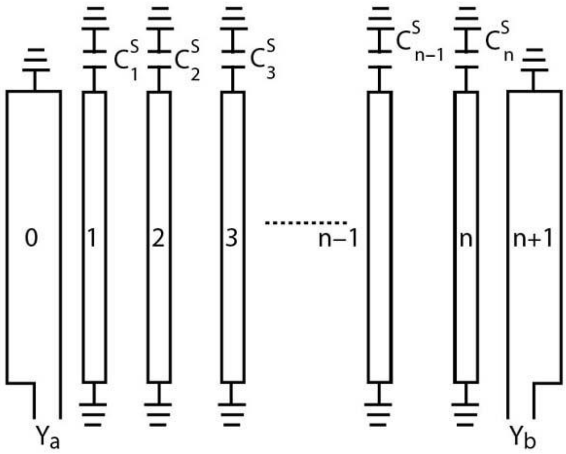

FIGURE 2.9. Topology of Combline Filter

Meanwhile Anurag also mentioned that the topology of combline filter includes the TEM transmission lines that will have one end short-circuited and the other end with a lumped capacitance C_0 between the ground. This enables the coupling between resonators to be fulfilled through fringing fields between the resonator lines. With the presence of the capacitors, the filter's electrical length is less than 90°, which enables the combline filter to have smaller and compact filter structure.

2.7 Lossy Filters

In order to improve the selectivity in the designed filters, many have been focusing on filters with smaller size but having the performance improved. Various techniques have been researched such as the adaptive pre-distortion technique optimizes filter elements by assumptions of same filter topology. However, this technique will provide degraded return loss performance. Non-reciprocal devices are also being suggested in order to compensate loss experienced by the filters. This in turn will not be able to achieve the criteria of creating filters with smaller size but better performance with the addition of more devices. Guyette, Hunter and Pollard [11] mentioned on lossy circuit extraction techniques as one of the techniques in including loss. Through this technique, the modified topology with added loss is used together with non-uniform dissipation. It is expected to improve the response and return loss of the filter. Unfortunately, this synthesis method can only be applied on symmetrical filter networks which are filters with odd and even mode analysis only [12]. Incorporation of loss factors such as conductor and dielectric losses in designing filters are important to prevent the response gap between ideal (theoretical) and realistic (experimental) parameters.

Losses which are to be incorporated while designing filters such as conductor loss (α_c) and dielectric loss (α_d) can also be known as attenuation in transmission line. The losses are mainly being associated with finite conductivity. Conductor loss depends on the field distribution within the transmission line and can be calculated by considering the penetration of magnetic flux onto each conducting surface that will affect the increase in inductance value separately. Therefore, it varies with the different types of transmission line being implemented. On the other hand, attenuation due to lossy dielectric can be determined using the propagation constant provided that the transmission line is of homogeneous dielectric.

Propagation constant can generally be expressed as the following:

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{2.10}$$

For complex propagation constant, it can also be expressed as:

$$\gamma = \sqrt{(j\omega L)(j\omega C)\left(1 + \frac{R}{j\omega L}\right)\left(1 + \frac{G}{j\omega C}\right)}$$

$$= j\omega\sqrt{LC}\sqrt{1 - j\left(\frac{R}{\omega L} + \frac{G}{\omega C}\right) - \frac{RG}{\omega^2 LC}} \tag{2.11}$$

CHAPTER 3

METHODOLOGY AND PROJECT WORK

3.1. Research Methodology and Project Activities

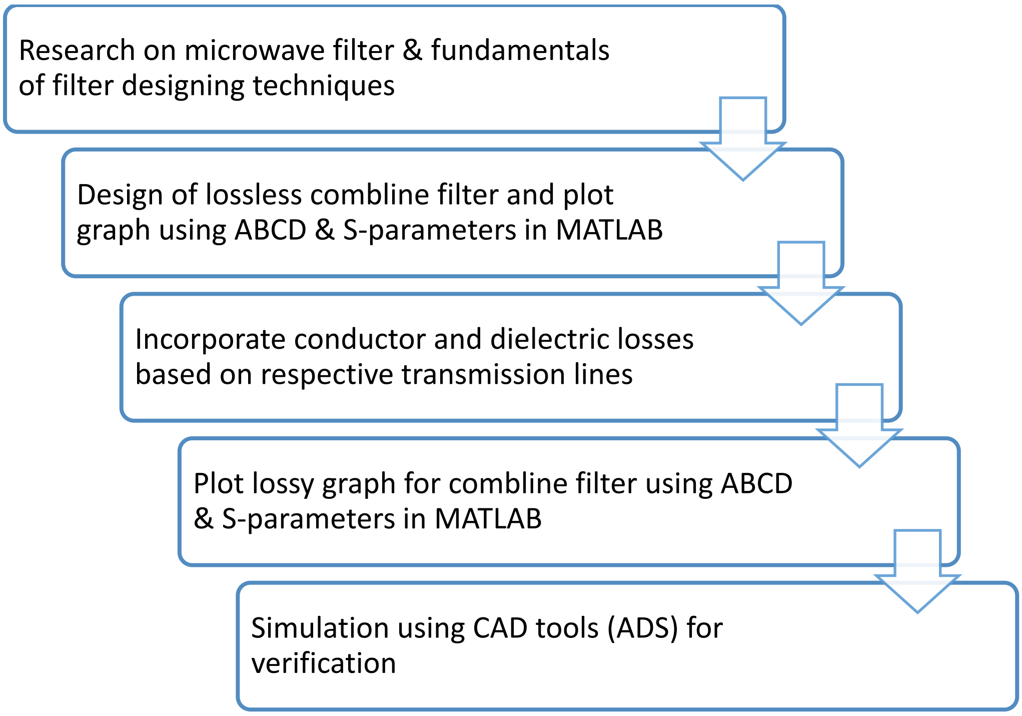

FIGURE 3.1. Flow of Project Work

Firstly, the working principle and overall theory of microwave filter system are to be researched and understood before progressing to the next step. Next, the fundamentals of filter designing techniques are also focused in order to start off with the first design of combline filter topology due to the focus of high-frequencies and impedance levels for transmission line prototype. The filter circuit to be developed until this stage will still be under ideal case response, before taking into consideration of the losses in real life situations. Simulation will be done using MATLAB, Maple or ADS for the lossless combline filter. Once done, the incorporation of losses into the lossless filter circuit will take place and proceed with simulation using CAD tools for modelling purposes.

Few different transmission mediums are used for implementation of the designed lossy combline filter. Simulations using ADS are used to compare and verify the modelling performed in MATLAB.

3.2. Project Key Milestones

i. *Literature review*

- Working principles and theory on microwave filter are further researched, at the same time the design techniques of combline filters are also to be focused.

ii. *Developing lossy combline filter*

- Lossless combline filter is to be derived and the ideal case frequency response will be plotted using MATLAB.
- Incorporation loss to the filter designed for practical realization purposes.
- Various transmission lines are included into the modelling.

iii. *Project simulation*

- Simulation of lossy combline filter using CAD tools for analysis, modelling and verification purposes as well.

3.3. Gantt Chart

ID	Task Name	Start	Finish	Duration
1	Proposal of Title	9/24/2014	9/24/2014	1d
2	Approval of Title	9/29/2014	9/29/2014	1d
3	Preliminary Research Work	9/30/2014	11/3/2014	5w
4	Literature Review	10/28/2014	10/28/2014	0w
5	Studies on Microwave Filter (Working Theory)	9/30/2014	10/6/2014	1w
6	Research on Techniques of Filter Design	10/6/2014	10/19/2014	2w
7	Understanding Combline Filter	10/20/2014	11/2/2014	2w
8	Submission of Extended Proposal	10/27/2014	10/31/2014	5d
9	Design Development of Ideal Filter	11/3/2014	11/30/2014	4w
10	Proposal Defense Presentation	11/10/2014	11/21/2014	1w 5d
11	Synthesis of Lossy Combline Filter	12/1/2014	12/28/2014	4w
12	Checkpoint for Filter Synthesize	12/15/2014	12/15/2014	0w
13	Submission of Interim Draft Report	12/15/2014	12/19/2014	5d
14	Submission of Interim Report	12/22/2014	12/26/2014	5d
15	Simulation of Designed Filter using CAD Tools	1/12/2015	2/8/2015	4w
16	Checkpoint for Simulation	1/26/2015	1/26/2015	0w
17	Submission of Progress Report	2/23/2015	2/27/2015	5d
18	Analysis on Various Transmission Medium	2/9/2015	3/13/2015	4w 5d
19	Pre-Sedex	3/16/2015	3/20/2015	5d
20	Submission of Final Draft Report	3/23/2015	3/27/2015	5d
21	Submission of Dissertation (soft bound) & Technical Paper	3/30/2015	4/3/2015	5d
22	Viva	4/6/2015	4/10/2015	5d
23	Submission of Hard Bound Project Dissertation	4/13/2015	4/17/2015	5d

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Ideal Combline Filter

An ideal combline filter of degree 4, with center frequency of 2GHz and bandwidth of 40MHz has been designed and simulated using MATLAB. The following formulas are used to calculate the lowpass element values before transforming into bandpass filter.

$$C_r = \frac{2}{\eta}\sin\left[\frac{(2r-1)\pi}{2N}\right] \tag{4.1}$$

$$K_{R,R+1} = \frac{\sqrt{\eta^2 + \sin(\frac{R\pi}{N})}}{\eta} \tag{4.2}$$

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

With that, w_0 and Δw can be obtained following by α and β with the following formulas, the choice of electrical length θ is chosen to be 50º which is also equivalent to 0.8726 radians to achieve optimum response.

$$\alpha = \frac{2\omega_o\tan(\theta_o)}{\Delta\omega\{\tan(\theta_o) + \theta_o[1 + \tan^2(\theta_o)]\}} \tag{4.3}$$

$$\beta = \frac{1}{\omega_o\tan(\theta_o)} \tag{4.4}$$

Following the values of α and β, Y_{rr}=1. Values of n which will be used in obtaining the admittances and impedances of the combline circuit are calculated with the formulas below.

$$Y_{rr} = Cw_0 \tan(\theta_0) \tag{4.5}$$

$$n_r = [\frac{\propto C_L \tan(\theta_0)}{Y_{rr}}]^{\frac{1}{2}} \qquad where\ r = 1, \dots, N \tag{4.6}$$

$$Y_{r,r+1} = \left[\frac{K_{r,r+1} \tan(\theta_0)}{n_r n_{r+1}}\right] \qquad where\ r = 1, \dots, N-1 \tag{4.7}$$

$$Y_r = Y_{rr} - Y_{r-1,r} - Y_{r,r+1} \qquad where\ r = 2, \dots, N-1 \tag{4.8}$$

$$Y_1 = Y_N = Y_{11} - Y_{12} + \frac{1}{{n_1}^2} - \frac{1}{n_1 \cos(\theta_0)} \qquad where\ r = 1\ and\ N \tag{4.9}$$

$$Y_0 = Y_{N+1} = 1 - \frac{1}{n_1 \cos(\theta_0)} \tag{4.10}$$

$$Y_{01} = Y_{N,N+1} = \frac{1}{n_1 \cos(\theta_0)} \tag{4.11}$$

After calculating the values of the respective admittances, it is being scaled to the impedances defined at 50Ω by dividing the admittances or multiplying the impedances. The table below shows the values of impedances scaled.

TABLE 4.1. Values of Scaled Impedances

Elements	Values
$Z_0 = Z_5$	66.30 Ω
$Z_1 = Z_4$	66.33 Ω
$Z_2 = Z_3$	52.34 Ω
$Z_{01} = Z_{45}$	203.42 Ω
$Z_{12} = Z_{34}$	1976.29 Ω
Z_{23}	2577.32 Ω
C	1.3356 pF

By having all the impedances values scaled, the equivalent circuit of a 4th degree combline filter can be produced as Figure 4.1.

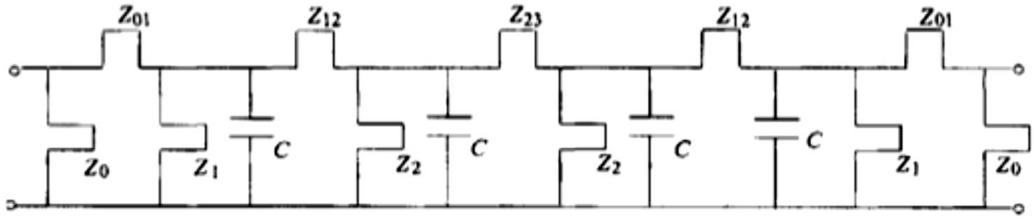

FIGURE 4.1. Equivalent Circuit of A 4th Degree Combline Filter

The modelled 4th degree ideal combline filter has the simulated response as shown in Figure 4.2.

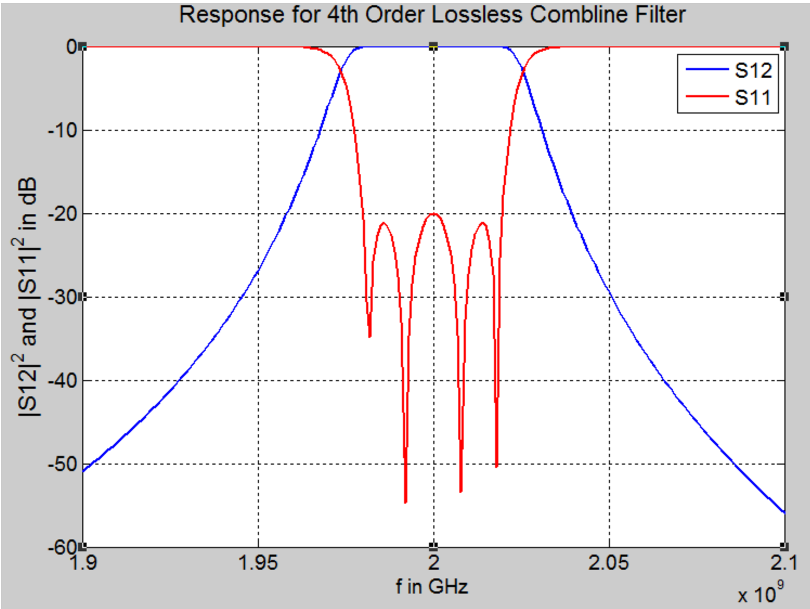

FIGURE 4.2. Simulated Response for An Ideal 4th Degree Combline Filter

From the simulated response, it can be concluded as an ideal case as there is no loss. The response of S_{21} which is the forward transmission coefficient is at 0dB. S_{21} is a ratio of output reflected wave to the input incident wave. By having 0dB or 1, it means that there is no loss hence, it is an ideal 4th degree combline filter whereas, the return loss of the simulated response shows there is ripple for S_{11} at -20dB.

The simulated response is also verified by designing and simulating the response using ADS. Figure 4.3 and 4.4 shows the schematic circuit and response plotted using ADS. It is the same as obtained in MATLAB. This confirmed the modelling is a success up to this stage.

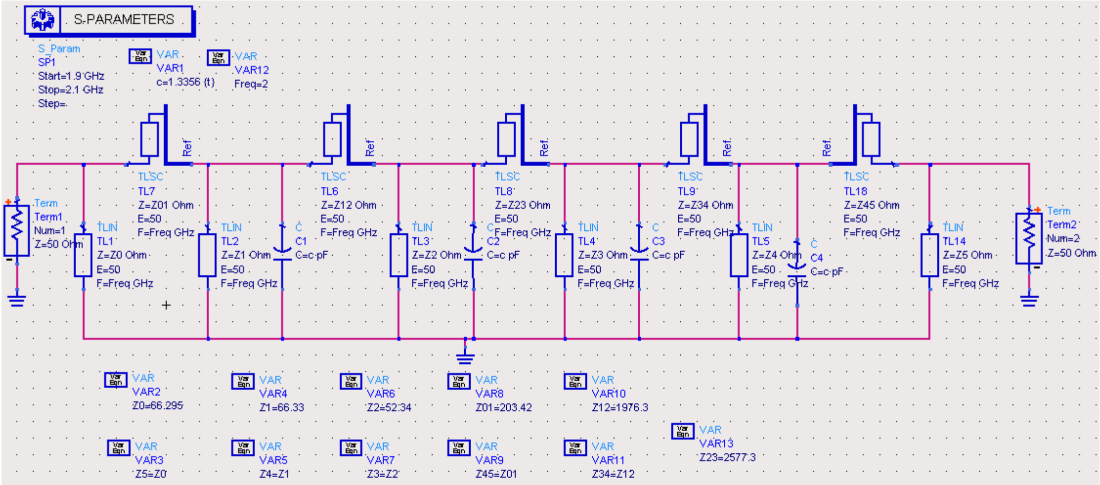

FIGURE 4.3. Schematic Circuit of a 4th Degree Combline Filter in ADS

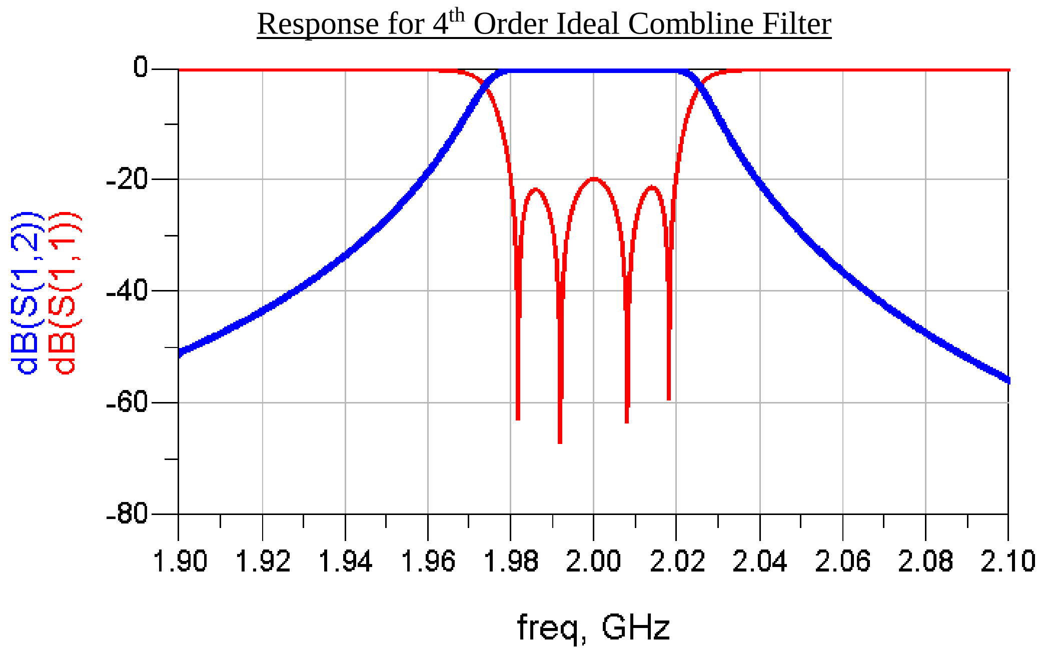

FIGURE 4.4. Simulated Response for An Ideal 4th Degree Combline Filter

4.2 Lossy Combline Filter

As mentioned in the previous section, attenuation within a transmission line are mainly due to lossy dielectric which is also dielectric loss (α_d) and conductor loss (α_c). If both of the losses exist in the selected types of transmission media, the total attenuation constant would be the summation of both $\alpha = \alpha_c + \alpha_d$. According to Pozar [7], the complex propagation constant can be expressed as:

$\gamma = \alpha_d + j\beta$

$= \sqrt{{k^2}_c - k^2}$

$$= \sqrt{{k^2}_c - {\omega^2}_{\mu_0\epsilon_0\epsilon_r}(1 - j\tan\delta)} \quad (4.12)$$

It can be further reduced to the following since most of the dielectric materials possesses small losses where $\tan\delta \ll 1$.

$$\gamma = \sqrt{k_c^2 - k^2 + jk^2\tan\delta}$$

$$\simeq \sqrt{k_c^2 - k^2} + \frac{jk^2\tan\delta}{2\sqrt{k_c^2 - k^2}}$$

$$= \frac{k^2\tan\delta}{2\beta} + j\beta, \quad (4.13)$$

Hence, the attenuation constant caused by dielectric loss (α_d) will be:

$$\alpha_d = \frac{k\ \tan\delta}{2}\ \text{(Np/m)} \quad (4.14)$$

where $k = \frac{2\pi f\sqrt{\epsilon_r}}{c}$ and c is the speed of light which equals to 3 x $10^8 ms^{-1}$.

4.3 Various Transmission Lines

4.3.1 Coaxial Line

Coaxial transmission line possesses only conductor losses (α_c) which is greatly affected by the field distribution in the line. It can be calculated by considering the penetration of magnetic flux onto each conducting surface using the formula as follow:

$$\alpha_c = \frac{R_s}{2\ \eta\ \ln(\frac{b}{a})}\left(\frac{1}{a} + \frac{1}{b}\right) \quad (4.15)$$

where $\eta \approx 377\Omega$.

There is no dielectric loss for coaxial line as there is no homogeneous dielectric substrate for the coaxial line structure.

4.3.2 Stripline

For stripline which is another type of TEM line, the attenuation due to conductor loss are approximated as follows:

$$\alpha_c = \begin{cases} \dfrac{2.7 \times 10^{-3} R_s \epsilon_r Z_0}{30\pi(b-t)} A & \text{for } \sqrt{\epsilon_r} Z_0 < 120\ \Omega \\ \dfrac{0.16 R_s}{Z_0 b} B & \text{for } \sqrt{\epsilon_r} Z_0 > 120\ \Omega \end{cases} \tag{4.16}$$

where

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

$$B = 1 + \frac{b}{(0.5W + 0.7t)}\left(0.5 + \frac{0.414t}{W} + \frac{1}{2\pi}\ln\frac{4\pi W}{t}\right)$$

and t represents the thickness of the strip, $R_s = \sqrt{\frac{\omega\mu_0}{2\sigma}}$ is defined as the loss tangent of the dielectric and $\mu_0 = 4\pi \times 10^7$.

The values of σ to be used along with the formulas in determining R_s depends on the material type being used in the transmission line. Some of the general constants are as Table 4.2.

TABLE 4.2. Surface Resistivity (Parameters) Dependent on Materials Used

Type of Materials	Surface Resistivity (R_s) (S/m)
Copper	5.8×10^7
Gold	4.1×10^7
Aluminium	3.8×10^7
Silver	6.2×10^7

It is due to the number of conductors in stripline is two and one homogeneous dielectric, it is able to support TEM just as the coaxial line and parallel plate waveguide. With an extra good point, stripline has the ability to support higher order waveguide modes in which it outshines the others in this area.

4.3.3 Microstrip Line

Proceeding next to the microstrip line, most of its field lines in the dielectric region are between the strip conductor and the ground plane, with some of the air region above the substrate. The difference between microstrip line and stripline is that the field of stripline are being restricted within a homogeneous dielectric area.

By considering microstrip line as a quasi-TEM line, the dielectric loss ($\propto_d$) is

$$\alpha_d = \frac{k_0 \epsilon_r (\epsilon_e - 1) \tan \delta}{2\sqrt{\epsilon_e}(\epsilon_r - 1)} \text{ Np/m} \tag{4.17}$$

where $\tan \delta$ is defined as the loss tangent of the dielectric.

The conductor loss ($\propto_c$) is approximated to be

$$\alpha_c = \frac{R_s}{Z_0 W} \text{ Np/m.} \tag{4.18}$$

where $R_s = \sqrt{\frac{\omega \mu_0}{2\sigma}}$ is defined as the loss tangent of the dielectric and $\mu_0 = 4\pi \text{ x } 10^7$

4.3.4 Suspended Substrate Stripline (SSSL)

In SSSL, a minimum of dielectric is used in order to minimize the effect of dielectric losses in the passband. The conductor losses in SSSL can be calculated using the following formula:

$$\propto_c = \frac{0.0231\, R_s \epsilon_r Z_0}{30\pi\,(b-t)}\ (A + B) \tag{4.19}$$

where

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

for $Z_0\sqrt{\epsilon_r}\left(1 + \frac{2.3t}{b}\right) \geq 120\Omega$,

$$B = \frac{0.35 - \frac{w}{b}}{(b-t)\left(1 + \frac{12t}{b}\right)^2}\left[\frac{t}{b}\,(17.45b + 35w) - 9w + 5.85 - 32.4\,\frac{t^2}{b}\right]$$

whereas for $Z_0\sqrt{\epsilon_r}\left(1 + \frac{2.3t}{b}\right) < 120\Omega$,

$$B = 0$$

The table 4.3 summarizes the types of losses associated with the transmission lines realized using combline filter.

TABLE 4.3. Types of Losses Associated with Transmission Lines

Type of Transmission Lines	**Conductor Loss** ($\propto_c$)	**Dielectric Loss** ($\propto_d$)
Coaxial	$\frac{R_s}{2\eta \ln(\frac{b}{a})}(\frac{1}{a} + \frac{1}{b})$	-
Microstrip	$\frac{R_s}{Z_o w}$	$\frac{k_o \varepsilon_r (\varepsilon_e - 1) \tan \delta}{2\sqrt{\varepsilon_e}\,(\varepsilon_r - 1)}$
Stripline	$\frac{2.7\ x\ 10^{-3} R_s \varepsilon_r Z_o}{30\pi\,(b-t)} A$	$\frac{k \tan \delta}{2}$
Suspended Substrate Stripline (SSSL)	$\frac{0.0231\ R_s \varepsilon_r Z_o}{30\pi\,(b-t)}(A+B)$	-

4.4 Modelling of Lossy Combline Filter in MATLAB

After the success of modelling an ideal combline filter in MATLAB and verified using ADS, the modelling is further extended in including respective losses for various transmission lines as listed in Table 4.3.

The program starts by requesting user's input for desired order of filter, center frequency, passband bandwidth, characteristic impedance (Z_o) and etc. The extended modelling also requires users to select the desired type of transmission lines for response to be simulated and the type of materials used in order to determine the surface resistivity in computing the conductor losses. Figure 4.5 shows the sample user interface.

```
Order of the filter : 4
Center frequency fo [GHz]: 2
Passband bandwidth [GHz]: 0.04
Characteristic Impedance (Zo) [Ohms]: 50
Passband Return Loss [dB]: 20
Q-factor: 100

 Choices of Transmission Line:
 1. Coaxial
 2. Microstrip
 3. Stripline
 4. Suspended Substrate Stripline
               2

 Choices of Electrical Conductivity Material:
 1. Aluminium
 2. Gold
 3. Silver
               1
```

FIGURE 4.5. User Interface in MATLAB

The parameters used in computing the losses are able to be calculated through the information input by users. For instance, the Q-factor information is used in determining the value of a and b.

The program will run based on the selections and compute the values, followed by simulating the response graph. Figure 4.6 shows the response as input by user in Figure 4.5.

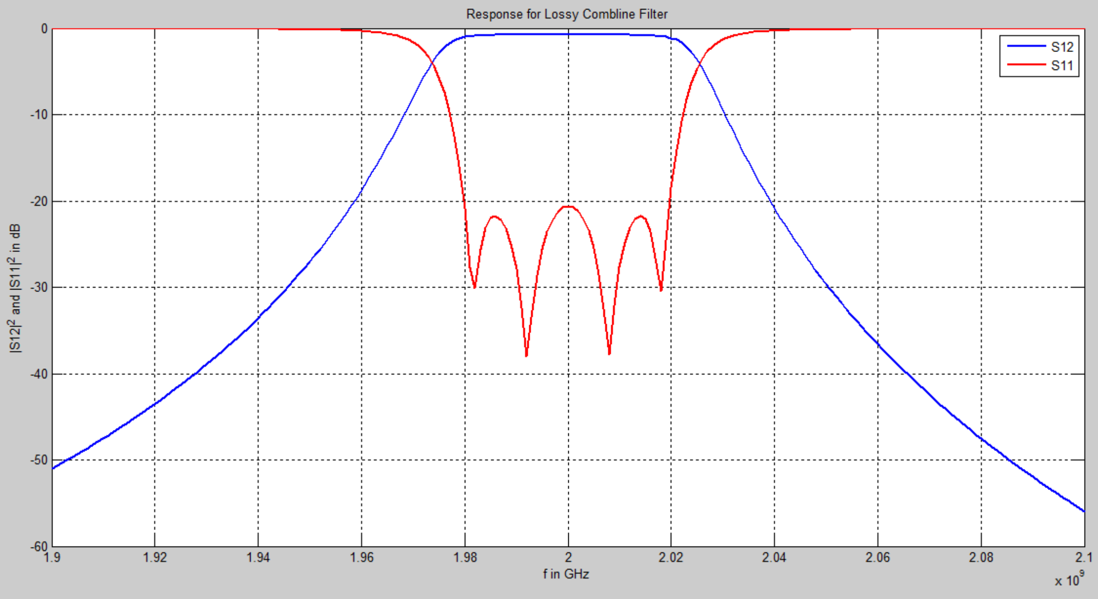

FIGURE 4.6. Response for Lossy Microstrip in MATLAB

From Figure 4.6, it is able to be observed that the passband for S_{12} is lowered and no longer at 0dB, in which losses are being incorporated into the simulation accordingly. This response is also further verified using ADS.

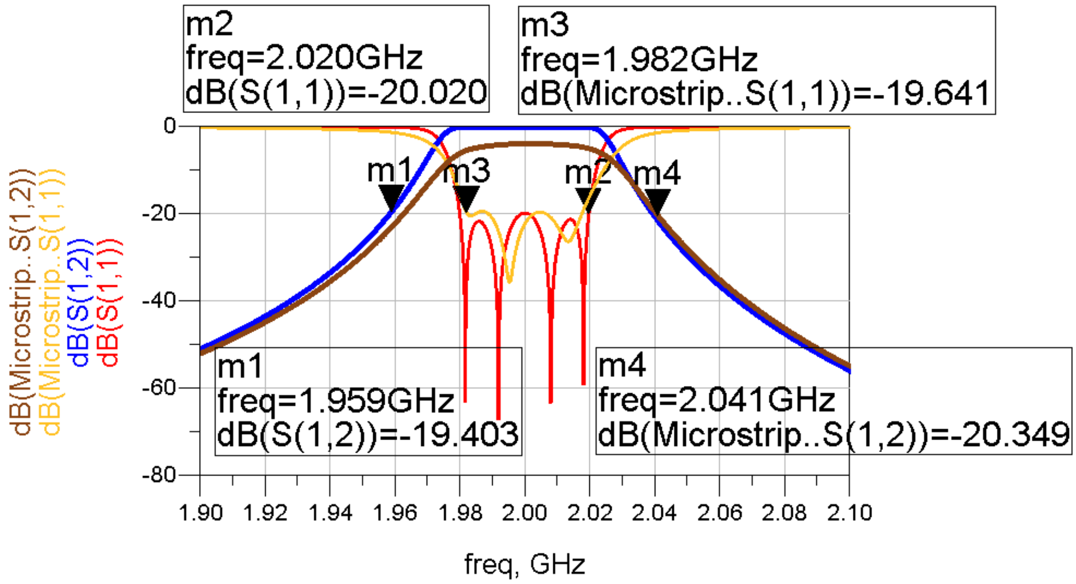

FIGURE 4.7. Response for Ideal and Lossy Microstrip in ADS

Both the ideal and lossy responses are plotted in order for a clearer view of the losses being incorporated while the user requirements are still maintained. From the results, it can be concluded that the modelling performed in MATLAB works. By performing the modelling in MATLAB, it is observed also that by using MATLAB, it requires less processing time to plot a response as compared to using ADS. To be able to plot a response in ADS, it needs not only the values computed for the impedances, but also to come out with the schematic circuit before being able to plot the response graph. Basic knowledge of ADS is also required to be able to use ADS. Through MATLAB, the user's input requirements are the basic and the rest of the calculations for impedances will be taken care of and response graph can be obtained at the end. Modelling in MATLAB is greatly encouraged too due to the availability of the software in university compared to the expensive advanced designing software such as ADS.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

A lossless and lossy combline filter network was successfully developed and modelled in MATLAB. The objectives of the project are achieved by incorporating various losses accordingly to the transmission lines models in MATLAB. The process of gathering the accurate formula from many different sources and attempting to put them into MATLAB coding with reference to the variable frequency has proven to be a great challenge in the project. Even though it can easily be done using other CAD tools such as ADS, however the real programming within the software itself was not known. Hence, it could be the first to be able to model the similar ones through MATLAB programming.

From the beginning of the design and modelling process of combline filter, it has achieved practical realization in the end where the lossy part which includes the conductor and dielectric losses are incorporated into the designed filter. Thus, more accurate results can be produced. It is also hoped that through the success of this research, more reliable filter design parameters can be input by engineers in the industrial sector. The success of this research may also reduce the chances of malfunction of filter fabrication and cost used in re-fabricating the inaccurate filters can be reduced. Schematic circuits were designed using ADS for modelling purposes in verifying the results of the designed filter. With the help of those tools, simulations is able to be performed in shorter amount of time. Not forgetting that the modelling in MATLAB is also useful for students in university in their learning and research with the availability of MATLAB software in university compared to the expensive advanced design software such as ADS.

5.2 Recommendations

To fabricate and observe the results practically using various transmission lines, Computer Simulation Technology (CST) or Ansys High Frequency Structural Simulator (HFSS) software can be used in future with its powerful designing and analysis capability. Besides, it would be great to be able to directly import the values computed from the MATLAB into the CAD software which can proceed into realizing it practically by fabrication as the values are needed in order to design the layout for fabrication.

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