

**COMPUTER-AIDED DESIGN (CAD) AND  
FABRICATION OF MICROSTRIP  
LOW-PASS FILTER**

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**Presented in partial fulfilment for the award of  
*Bachelor of Engineering (Hons.) (Electrical)***

**Institut Teknologi MARA**

**40450 Shah Alam**

**SELANGOR**

**ZULKIFLI BIN HJ. MOHD SIDI**

**Faculty of Electrical Engineering**

**MARA Institute of Technology**

**40450 Shah Alam**

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## DECLARATION

**A report submitted to the Faculty of Electrical Engineering, MARA Institute of Technology in partial fulfilment for the award of Bachelor in Electrical Engineering (Hons).**

This thesis is approved by:

.....

**( DR. ZAIKI BIN HJ. AWANG )**

**Project Supervisor**

Date: .....

## **DEDICATED TO**

With the name of ALLAH S.W.T, and with the help of ALLAH. All good ascription's, devotions, good expressions, prayers are for ALLAH. I bear witness that there is no god save ALLAH alone, no partners unto Him, and I bear witness that Muhammad is as his servant and His Messenger, sent him along with the truth, as giver of glad tidings and as a Warner, and to tell that the hour is fast-approaching, no doubt in it. Peace is on you, the Prophet, and Allah's mercy and His blessings. Peace is on us and on Allah's upright servants. ALLAH, forgives me and straighten me.

And

I would like to dedicate this success specially to my wife and the children, Pn. Hashimah and Ahmad Fathul 'Izzat & Nur Nadiah 'Izzati who is committed to see me as an engineer and understanding me being a husband, dad and a student, hopefully me as a role model to them.

THANK TO ALLAH, MAY ALLAH BE WITH US.

## **ACKNOWLEDGEMENT**

Firstly and foremost, I would like to take this occasion to express my sincere gratitude and appreciation to my project supervisor and my advisor Dr. Zaiki b. Hj. Awang and Dr. Nafizah Goriman Khan (SIRIM) respectively, whose patience, inspiration, contribution of precious ideas, proposals, advise, support, committed, encouragement and constant guidance has help me to successfully complete the project and this thesis. Appreciation also goes to laboratory technician, especially En. Azman and En. Fauzi and friends for their Willingness Corporation and assistance my project.

Finally, I would like to thanks to all of you.

**MAY ALLAH BLESS YOU ALL.**

## ABSTRACT

The purpose of this project is to design, simulate, fabricate and measure or analysis the characteristics of a '*Microstrip Low-Pass Filter*' operating at microwave frequency by using *Computer-Aided Design (CAD)*. This Low-Pass filter should has a minimum '*Return Loss*' 15dB over the frequency range of 0~2 GHz with minimum '*Attenuation*' 15dB at 3 GHz. The Minimum and Maximum line impedance are 25  $\Omega$  and 90  $\Omega$  respectively, also known as Low and High impedance. The type of this microwave filter are called '*Maximally Flat*' (*Butterworth*), which is having often been reputed to have less delay distortion than other type of microwave filter, '*Chebyshev (Equal-Ripple)*' [2].

Material has been used are '*Duroid/Rogers 5870*' with a 0.5mm thickness and '*relative permittivity*' ( $\epsilon_r$ ) 2.33. By corporation with Computer-Aided Design (CAD) '*HP EEsof TouchStone*' (*Libra*) software, the simulation will eliminate many tedious steps and save a time to draw actual stripline before doing fabrication when conventional method was compared.

This project will present the synthesis and design of low-pass prototype microwave filter. The synthesis is done by CAD, which is better to used in modern day. This microstrip is locally fabricated in Fabrication Laboratory at ITM, Shah Alam on '*Duroid 5870*' planar circuit and then measured by Wiltron 562 Scalar Network Analyser.

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**CHAPTER 1:**  
**INTRODUCTION**

## 1.1 OBJECTIVE & INTRODUCTION TO THE PROJECT

The purpose of this project is to design, analyse, simulate, fabricate and measure the *low-pass filter* as specification need, which is having frequency range between 0 to 2 GHz, with minimum return loss and attenuation are 15 dB and 15 dB respectively. The main function of the filter is to pass only those frequencies in the assigned operating range and rejects all others. In this case, more than 2 GHz will be rejected, below than that can pass through.

Presented the synthesis and designing a Butterworth *low-pass prototype* microwave filter by using *Insertion Loss Method* (will explain in future section). The synthesis is more convenient and smoothly done, all equipment and tools was provided by Faculty Electrical at ITM, and the circuit performance is simulated and optimised using the software '*HP Eesof Libra Touchstone*' to the intended circuit fabrication.

The circuit is then fabricated on microstrip laminate with substrate thickness of 0.5 mm. The materials type are '*RT/Duroid 5870*' or '*Roger's 5870*' which is relative dielectric constant ( $\epsilon_r$ ) is 2.33 also as know as '*PTFE (Polytetrafluorethylene) Teflon*'.

The source and load terminal will terminated by 50  $\Omega$  impedance. The series inductance's (L's) will be high impedance line (90  $\Omega$ ) and shunt capacitance's (C's) will be low impedance line (25  $\Omega$ ). A *Scalar Network Analyser (Wiltron 526)* is then used for measurement of the Low-Pass Filter (Butterworth type).

Thank you indeed giving to the Electrical Engineering Faculty of Institut Teknologi MARA, the credit should be given to the faculty management, because of the successfully development in set up facilities of microstrip fabrication. During the facilities set up, various kind of problem was occurs. Now, the right condition such as solution and chemical was determined. The microstrip '*Made in ITM*' was created.

These thesis reports also covered the satisfaction of fabrication procedure in ITM itself [1].

## **1.2 COMPUTER-AIDED DESIGN (CAD) OF MICROWAVE CIRCUITS**

Computers are powerful tools for the microwave designers in performing arduous and error-prone calculations. Computers as a tools to design many circuits and components faster and cheaper than conventional methods. To get high reliability standards, precisely characterised and less error to the designing circuits, Computer-Aided Design (CAD) becomes a better simulator in microwave technology, and it is cannot be separated. By CAD, user will eliminate trial and error, laborious mathematical calculations and delaying in drafting. CAD also allows rapid evaluation of many existing circuits, safe a time and cost saving. Furthermore, CAD has allowed many organisations to increase their productivity.

The advent of printed-circuit board (PCB) technology, microwave system also develop a stripline components and system with a technique of integrated circuit, called '*Monolithic Microwave Integrated Circuit*' (MMIC). It works in a planar single circuit board. Thus the use of connectors component is eliminated.

### **1.2.1 Monolithic Microwave Integrated Circuits (MMICs)**

Monolithic Microwave Integrated Circuits (MMICs) are an important ingredient in the design and fabrication of future sophisticated system such as radar and electronic countermeasure (ECM) systems. There is a module composed of hybrid circuits onto several substrate, such as transistors, capacitor, inductor etc. that has been fabricated by assembly of a number of lumped or distributed elements on which distributed microstrip lines have been formed.

Monolithic microwave integrated circuits (MMICs) are microcircuits fabricated on semiconducting substrates, using diffusion or ion implantation techniques. Because of very high-frequency circuits are used, the performance becomes critically dependent on the position and size of the various circuit elements.

## 1.2.2 CAD Procedure for Microwave design

To more systematic in using CAD, the flow diagram must be obtained.

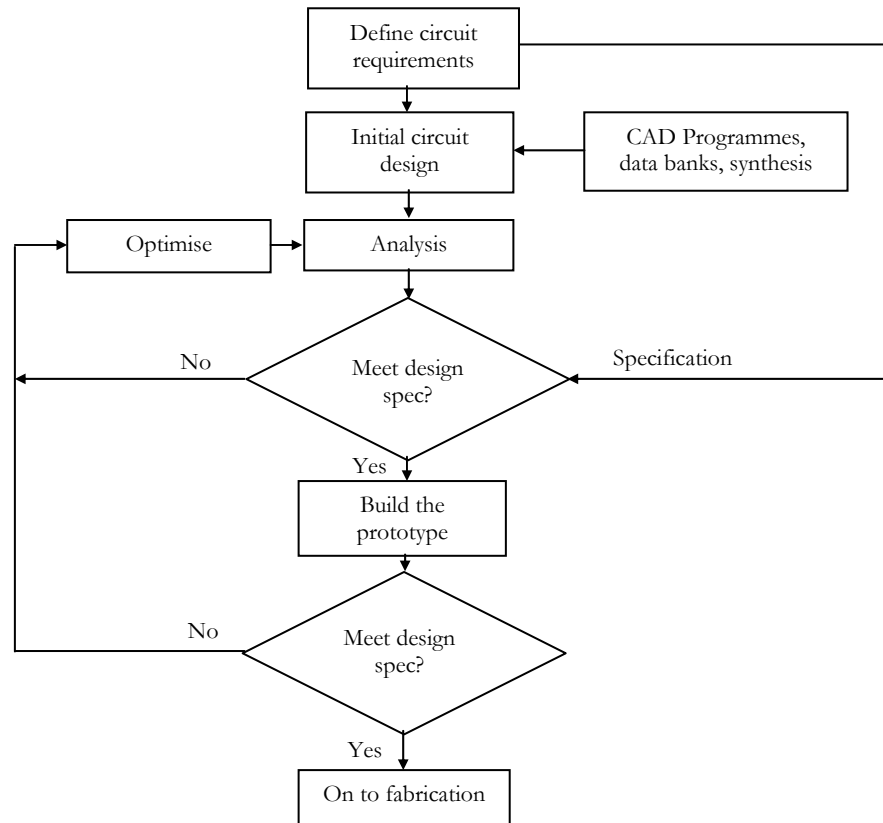


Figure 1.1: CAD Procedure

The flow diagram as a guided to the designer to obtained their strategy and getting a good result as required.

## 1.2.3 Why Need CAD for Analysis

The conventional methods or procedure for microwave circuit design has become increasingly difficult to use because of its iterative and empirical methods. There are considerations such as:

- The complexity of modern systems and demanding in precision and accurately of circuits design.

- The variety of active and passive devices is now available for achieving a circuit function. Difficulties in selective the appropriate device when using the empirical design.
- Difficulties to incorporate any changes in circuits fabricated by Microwave Integrated Circuit (MIC) technology.
- When using Breadboarded circuits, especially in MIC, are not notoriously inaccurate in predicting the performance of the final design.

To overcome performance of analysis, the evaluated circuits are using a CAD to analyse a circuit package. The sets are converting the components in the input file into numerical models for computer evaluation.

Optimisation is used to obtain the result of analysis after comparing with the given specifications. When the result are not satisfactory, certain parameters can be changed within the circuit in a systematic manner.

The sequences of analysis, comparison, and modification are performed iteratively until the specifications are met or the optimum performance of the circuit is achieved. The circuit is fabricated, and experimental measurements are made. Some modification may still be required, but the changes will be small, and the aim of CAD is to reduce these postdesign modifications to a minimum is realise.

#### **1.2.4 CAD Packages for Microwave Design**

Many software packages have become available in recent years, providing features noise figure, biasing lines and blocking capacitors. The user-friendly features of software make us easy to use and well maintained to the user.

*HP Eesof Libra Touchstone* (IBM PC-Compatible) is a fastest general-purpose of radio frequency (rf) and microwave circuit design, analysis and optimisation of the microwave circuits.

More than 80 elements are contained in its library, including microstrip, stripline, lumped elements and electronic device models. User can also define elements with their scattering matrix and two offers possibilities for adjustments optimisation algorithms for up to 15 variables. *Libra Touchstone* combines linear analysis in the frequency domain with time domain analysis of nonlinear elements. It also ideal for

analyse the digital circuits, driven by fast, periodic clock pulses, where the effects of the transmission line mismatch and delay line effects are critical.

#### **1.2.4.1 Optimisation**

The analysis software is inserted into an optimisation loop and used to calculate responses for successive sets of parameters, which are then compared to the desired response until the designs are met its requirements.

Gradient techniques are used with approximated design in analysis the circuits and calculated response is then compared to the specifications. A circuit's parameter is then slightly modified and the response circuits are determined.

#### **1.2.4.2 HP Eesof Libra Touchstone (Touchstone)**

There is three blocks are required to operate,

- Circuit (CKT)
- Output (OUT)
- Frequency (FRE)

Others block, which is optional depending on the type of analysis being performed.

- Dimension (DIM)
- Variable (VAR)
- Termination (TER)
- Process (PRO)
- Grid (GRID)
- Optimisation (OPT)
- Tolerance (TOL)

### 1.2.4.3 About Commonly Blocks Used

Starting comment lines with an '!'. This will give user as reminder to the purpose of the programmes at later date.

e.g.: I = 20\*LOG (L) ! Insertion Loss

The DIMension. As the default values and are included to assure the programmer of this fact.

e.g.: DIM  
FREQ GHZ  
IND NH  
CAP PF etc.

Circuit (CKT). Is a circuit descriptions.

e.g.: CKT  
CAP 1 0 C#0.1 0.9836 10 (1 & 0 as a node in circuit)

CKT block is ended by DEFining a two port (2P) between first and end nodes.

The OUTput block tell us, what parameters are needed for the various output formats.

GRID is using to autoranging the plotting a graph.

FREquency block, tells to TS what frequency range to compute over (There will be up to 100 frequency steps).

e.g.: FREQ  
SWEEP 0 20 0.5

OPTimisation block tells TS what to optimise

When use a lumped elements, RESistor and INDuctor, can be represented individually or as a series RL element.

## **1.2.5 Some Latest CAD Packages for RF and Microwave Design.**

### **1.2.5.1 HP Momentum (HP EEsof)**

- Accurately computes S-, Y-, or Z-parameters of arbitrarily shaped, multi-layer planar structures
- Eliminates grid restrictions associated with conventional planar electromagnetic simulators
- Fast simulations (second to minutes)
- Accounts for radiation (no box or enclosure required)
- Available integrated in both the RF and Microwave Design System.

The HP Momentum electromagnetic simulator accurately analyses multilayer, planar circuits in environments such as stripline, microstrip, suspended substrate, slot line and other layered dielectric media.

### **1.2.5.2 Electromagnetic Sight (EM Sight) – (Applied Wave Research, Inc.)**

- Easy-to-use EM simulator for high-frequency designers.
- Windows Driven enables a user to do something impossible with a linear simulator compute the coupling effects of neighbouring components at extremely high frequencies.
- Enables an operator with even minimal EM simulation experience to effectively model high-frequency circuits and structures.
- Can analyse the electrical behaviour of conducting circuit traces found on printed-circuit boards (PCBs) and in integrated circuits (ICs).
- Traces can be on different PCB layers
- PCB can be added to connect the different layers.
- Ideal for accurately modelling a variety of structures, including matching networks, spiral inductors, and couplers.

Fast full wave EM solver engine based on a modified spectral -domain method-of-moments (MoM) technique to accurately determine multiport scattering parameters.



Implements a fast-frequency-sweep (FFS) algorithm that provides an accurate extrapolation of frequency response with significantly less computational effort and time than required for a point-by-point frequency sweep.

#### **1.2.5.3 Microwave Office (Applied Wave Research, Inc.)**

*Microwave Office* is a completely new suite of RF/microwave design tools built from the ground up for operation in Windows® '95 and NT environments. Included in the suite are the Voltaire XL™ linear and nonlinear circuit simulator and the EM Sight™ full-wave, 3D electromagnetic (EM) simulator. The entire design solution is constructed using advanced object-oriented programming methods that result in impressive performance, reliability and ease of use.

### **1.3 MICROSTRIP**

Prior to 1965 nearly all microwave equipment utilised coaxial, waveguide, or parallel strip-line circuits. In recent years, with the introduction of monolithic microwave integrated circuits (MMICs), microstrip lines and coplanar strip lines have been used extensively.

Microstrip has become an attractive transmission line medium, especially where integration with chip devices and lumped elements is desired. A microstrip transmission line consists of a metallised strip and ground plane separated by a solid dielectric as shown in Fig. 1.2(a). This configuration has become a popular alternative to the coplanar and shielded strip lines and microstrip line, especially for miniature microwave circuits.

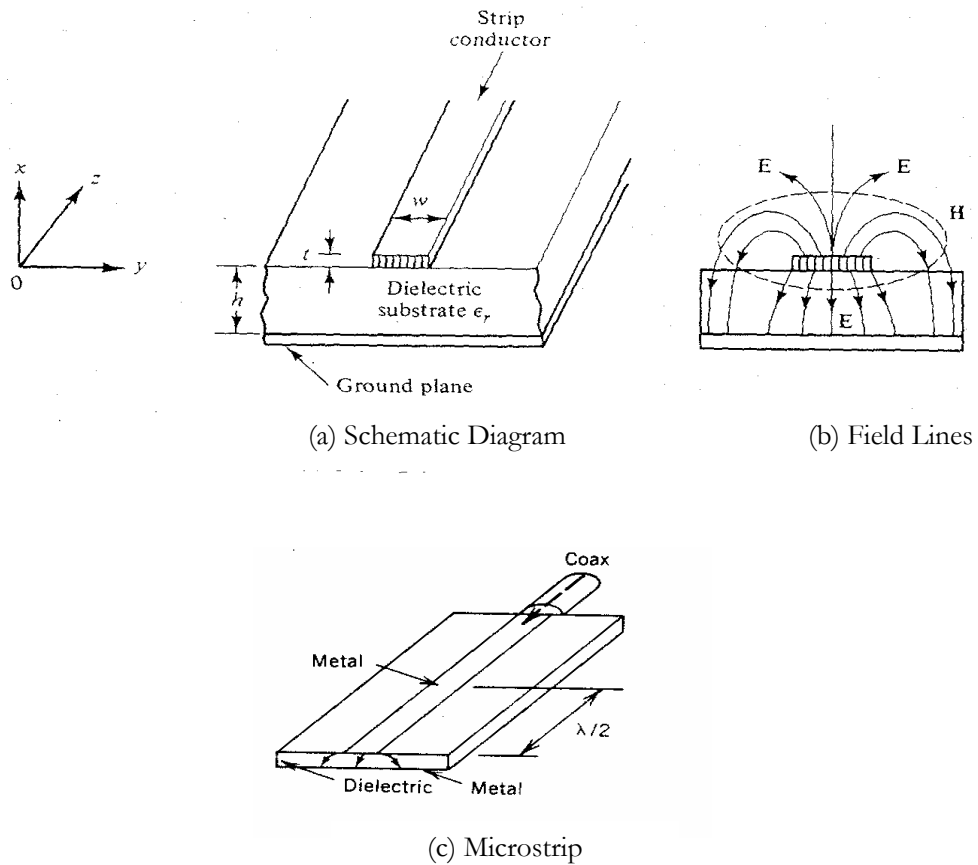


Fig. 1.2: Schematic and Construction of microstrip.

### 1.3.1 Why Microstrip Line Cannot Support a Pure & quasi-TEM

Microstrip has most of its field lines in dielectric region, it's concentrated between the strip conductor and the ground plane, and some fraction in the air region above the substrate. This reason give microstrip cannot support the pure TEM wave.

Since the phase velocity of TEM fields in dielectric region would be  $c/\sqrt{\epsilon_r}$ , but the phase velocity of TEM fields in the air region would be  $c$ . Thus, phase match at the dielectric –air interface would be impossible to attain for a TEM-type wave [6].

Modes on microstrip line are only *quasi-transverse* electric and magnetic (TEM). Thus the theory of TEM lines applies only approximately. At low frequencies the field configuration is quite close the TEM and pure TEM will be assumed. The problem of microstrip lines is a radiation losses, particularly in short circuit posts,

corners and so on. However, the use of thin, high-dielectric materials considerably reduces the radiation loss of the open strip.

A microstrip has an advantage over the balanced-strip line because the open strip has better interconnection features and easier fabrication. Another advantage is an active devices are used, especially transistors. Transistors can be placed on top of the board in many instances. Also any convenience for any circuit whose components must be mounted to the board. Any resistors, capacitors or diodes that are attached can be soldered directly onto the microstrip board.

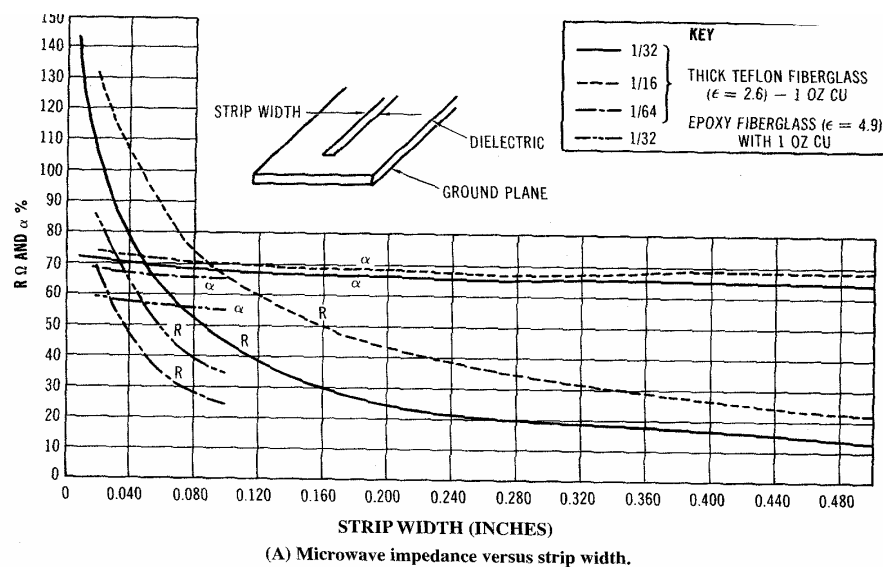


Fig. 1.3: Microstrip Characteristics<sup>1</sup>

To minimise isolation between circuits on the same substrate, the compartments will advise to mounted and prevent propagation of power radiated from the microstrip.

Microstrip is usually the lowest-cost media because all the circuitry is *photolithographically* etched on one side of the substrate and easy to mounted devices between two surface conductors. For devices generating the heat, a hole is drilled through the substrate to allow connection to the ground-supporting material.

Launching energy from coaxial to microstrip is done by connecting the coaxial centre conductor to the circuit conductor and the shield to the ground plane.

<sup>1</sup> Reference: Microwave Engineer's Handbook, Vol. 1, Artech House Inc. 1971

The function of planar microstrip as same as a Printed Circuit Board (PCB), which is doing at low frequencies. Frequency that allow in PCBs about a few hundred MegaHertz(MHz), if PCBs used in microwave frequency the losses become large and will affected to the performance of the systems. Microstrip can be used at microwave frequencies since it has a special dielectric substrate that confines the signal and hence less loss. About 100 GHz can use, when using very thin quartz substrate. Since it is easy to mount any components on microstrip due to the planar structure, so it is suitable to use it in solid state circuitry.

## **1.4 SUBSTRATE MATERIALS**

Edward A.Wolf and Roger Kaul said, there is two types of substrate materials being used;

- Hard
- Soft

The hard are fabricated from ceramic, crystalline materials, or semiconductors, whereas the soft substrates use ceramic or glass-filled Teflon [3].

### **1.4.1 Hard Substrate**

These types of substrates usually have a different thermal coefficient of expansion than the circuit fixture. And special metals and adhesives are needed to match between substrate and circuit fixture. It is limited to the small areas only (about  $1\text{cm}^2$ ) to prevent excessive stresses and applied in fine line resolution with smooth (polished) surfaces and low loss are required (at mm waves). These types of substrate circuits are more expensive to fabricate because they are 'brittle' and difficult to drill and cut to size for device and fixture mounting.

### **1.4.2 Soft Substrate**

It is available in range of dielectric constants, depending on materials. Teflon substrates is use for low dielectric constant such as glass microfibre reinforced

polytetrafluorethylene (PTFE Teflon) and Teflon-impregnated woven glass laminates, this is called 'Duroid' (by Rogers Corp., Chandler, AZ) and 'Di-Clad' (by Keene Corp., Bear, DE).

In this project, Duroid (PTFE Teflon)<sup>2</sup> is use as substrate materials. All Teflon dielectric is clad with various thickness of copper (Cu). The thickness is specified by the weight of copper. Soft substrates can follow the temperature-induced dimensional changes of the fixture, large circuits with a minimum of interconnection can be produced.

## 1.5 DIELECTRIC CONSTANT

### 1.5.1 Effective Dielectric Constant ( $\epsilon_{re}$ )

Some of the electric field on microstrip line passes through air (see Fig. 1.2(c)), the effective dielectric constant ( $\epsilon_{re}$ ) is less than bulk dielectric constant ( $\epsilon_r$ ) of the substrate.

And wavelength on the transmission line is,

$$\lambda = [ c / (f \sqrt{\epsilon_{re}}) ]$$

Where, c is the velocity of light in  $\epsilon_r = 1$ , and f is the frequency.

In free space, the propagation-delay time is

$$T_{df} = \sqrt{\mu_o \epsilon_o} = 3.333 \text{ ns/m}$$

Where,

$$\mu_o = 4\pi \times 10^{-7} \text{ H/m (Permeability in air)}$$

$$\epsilon_o = 8.854 \times 10^{-12} \text{ F/m (Permittivity in air)}$$

The  $\epsilon_{re}$  (Effective relative dielectric) constant for a microstrip line can be related to the  $\epsilon_r$  (Relative dielectric) constant of the board material. And Mr. DiGiacomo discovered an empirical equation as,

$$\epsilon_{re} = 0.475\epsilon_r + 0.67$$

Where,

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<sup>2</sup> My project materials

$\epsilon_r$  is the relative dielectric constant of the board materials and  $\epsilon_{re}$  is the effective relative dielectric constant for the microstrip line. In Fig.1.4, shown the effective relative dielectrics were occurring.

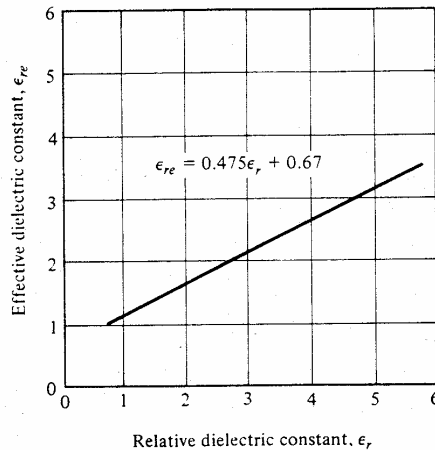


Fig. 1.4: Effective dielectric constant as a function of relative dielectric constant for a microstrip.

## 1.6 LOSS IN MICROSTRIP

There is a loss in microstrip that is commonly occurs under filter design. Approximation expressions are useful for designs and harder to quantify, can be neglected for design purposes.

### 1.6.1 Conductor Loss ( $\alpha_c$ )

The losses in microstrip circuits arise from conductor loss due to resistive losses in the strip.

It is a primary loss mechanism at low frequencies. The skin depth is a layer that is conducting a current. For a common metal such as Aluminium and Copper, the skin depth is about 0.8  $\mu\text{m}$  at 10 GHz. As the surface roughness increases, the current path increases and the conductor loss increases. And the conclusions are smooth substrates are essential for long circuits at high microwave and millimetre wave frequencies.

(eg.: Surface roughnesses  $< 0.25 \mu\text{m rms}$ , on soft substrates should be usable to 18 GHz).

### **1.6.2 Dielectric Loss ( $\alpha_d$ )**

It is due to the polarisation heating by time-varying fields in the substrate and radiation due to the antenna action of the microstrip. It arises because of reversal polarisation losses in the substrate. A measure of this loss mechanism is the loss tangent ( $\tan \delta$ ).

### **1.6.3 Radiation Loss ( $\alpha_r$ ) & Q**

Open stub, bends and discontinuities on transmission line excite higher-order modes, which radiate energy. Ratio of the reactive energy to radiated energy called the Q. The stub becomes a significant percentage of wavelength and experience as an antenna.

**CHAPTER 2:  
MICROWAVE FILTERS**



## 2.1 MICROWAVE FILTERS (LOW-PASS FILTER)

### 2.1.1 Introduction

Filters are used whenever there is something to be passed and something to get rid of. A filter is designed to remove something that unwanted and pass on what is wanted.

A microwave filter is a two-port device that plays the important role of controlling the frequency response at certain point at cross section in a microwave system, letting a band of frequencies pass through while rejecting frequencies in another bands. The low frequencies may be rejected with a *high-pass filter*, the high frequencies may be rejected with a *low-pass filter*, or all frequencies except a specific band may be rejected with a *band-pass filter*.

Filters are widely used in communication and radar system, in field test units and in laboratory measurement equipment.

Filters are also commonly used for separating frequencies in duplexers or multiplexers and as a harmonics removal in oscillators or amplifiers. Other tasks that can done by filters are to reduce a noise and reject signals at particular frequencies in bandstop filter applications. The application dictates whether the filter will have lowpass, highpass, bandpass or bandstop characteristics.

### 2.1.2 Ideal Microwave Filters

The *low-pass filters* can be designed from the classical lumped element prototyped circuits and may be either fabricated in lumped element form or transformed into equivalent transmission line networks.

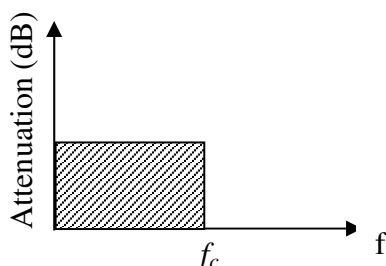


Fig. 2.1: Low-pass filter

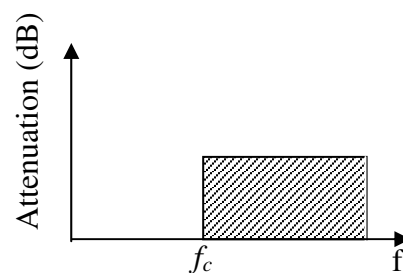


Fig. 2.2: High-pass filter

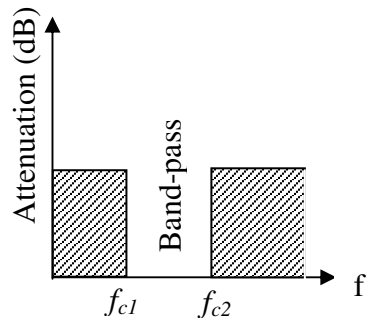


Fig. 2.3: Band-pass filter

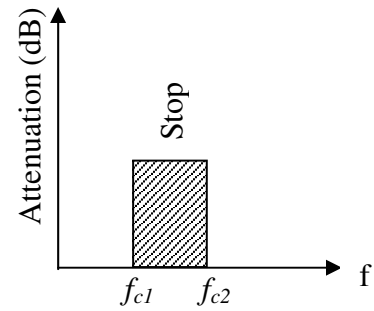


Fig. 2.4: Band-stop filter

The ideal *high-pass filter* prevents transmission below some cut-off frequencies and transmits all signals above it.

The *band-pass filter* passes all signals at frequencies between two frequencies and reflects signals at frequencies outside this band while the *band-stop filter* reflects all signals over a frequency outside it.

### 2.1.3 How To Designed Filters

Filters are designed using two methods:

- Image Parameter Method
- Insertion Loss Method

#### 2.1.3.1 Image Parameter Method

This is consist of cascade of simpler two-port filter sections to provide the desired cut-off frequencies and attenuation characteristic, but do not allow the specification of a frequency response over the complete operating range. Sound like a simple, but this procedure often uses much iteration to achieve the desired results.

#### 2.1.3.2 Insertion Loss Method

This is more modern procedure than Image Parameter Method, this is using network synthesis techniques to design filters with a completely specified frequency response. This type of designed is simplified by beginning with low-pass filter prototypes which

are normalised in terms of impedance and frequency. And of course, transformations are then applied to convert into desirable filters such as High-pass, Band-pass and Band-stop.

Both methods of filter design provide lumped-element circuits. The Insertion Loss method allows filter performance to be improved in a straightforward manner. The designs of low-pass filter prototypes are normalised in term of impedance and frequency and are able transform into desirable filter and also modification to distributed elements consisting of transmission line section.

The normalisation simplified the design for arbitrary frequencies, impedance and types of filters (i.e. High-pass, Band-stop and Band-pass). The low-pass prototypes are then scaled to the desired frequency and impedance. And the lumped element components are then replaced with the distributed circuit elements for implementation.

#### 2.1.4 Low-Pass Filters

This filter passes all frequencies below a certain frequency and rejects those above. Fig. 2.3 shows a low-pass filter response. The *passband* of this filter can be considered from zero to the portion termed *cut-off frequency* ( $f_c$ ). Generally, zero frequency as dc. The filter will, in fact, pass dc since it consists of series inductance and shunt capacitance. This equivalent circuit shown in Fig. 2.2. With such a configuration dc could be passed easily through this filter.

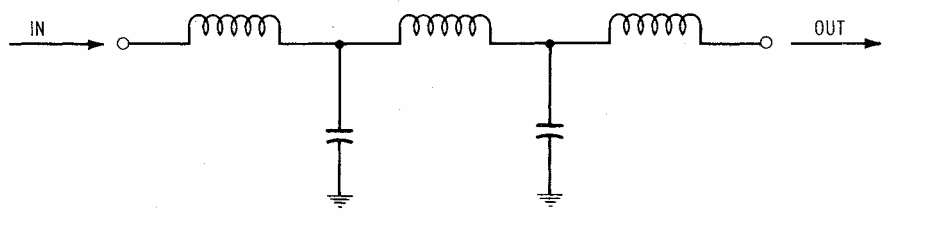


Fig. 2.2: The example of Low pass filter equivalent circuit

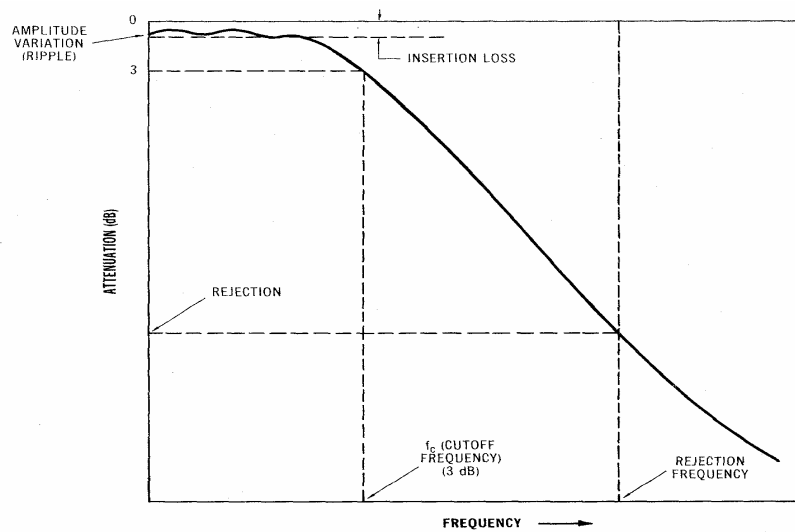


Fig. 2.3: Low pass filter response

Cut-off frequency ( $f_c$ ) is a term has been used many times in any design of filters. This frequency is when the response on 3 dB (half power below the insertion loss of the filter), to where the filter begins to take on the characteristics it is designed to have. Below this frequency the filter has low loss and is considered to be in its passband. Above this frequency there is ever-increasing loss as approaching the rejection frequency and an ultimate attenuation.

As example, if wanted to pass all frequencies below 1.0 GHz, do not specify a *lowpass filter* (LPF) as having  $f_c = 1.0$  GHz too, because at 1.0 GHz the response will be down 3 dB as shown in Fig. 2.3. The filter should have extra cut-off frequency above 1.0 GHz, so that the required frequencies will be in the low-loss passband.



Fig. 2.4: Physical Circuit Low-pass Filter

## 2.2 The Theories of Low-pass Filter Responses

### 2.2.1 Type of response

To realise this low-pass Butterworth filter at 2 GHz cut-off frequency, insertion loss and return loss response shows in Fig. 2.5 (in dB) and Fig. 2.6 (in magnitude).

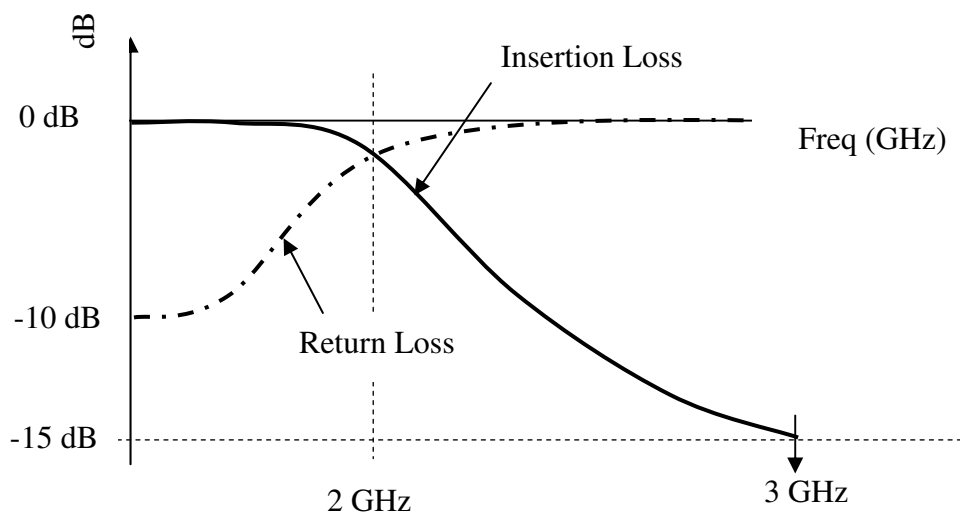


Fig. 2.5: The approximation of return loss and insertion loss in dB.

Theoretically,  $f_c$  at 2 GHz and 15 dB of minimum attenuation at 3 GHz as showed in Fig. 2.5 above. That figure shows the actual response should be getting in this project.

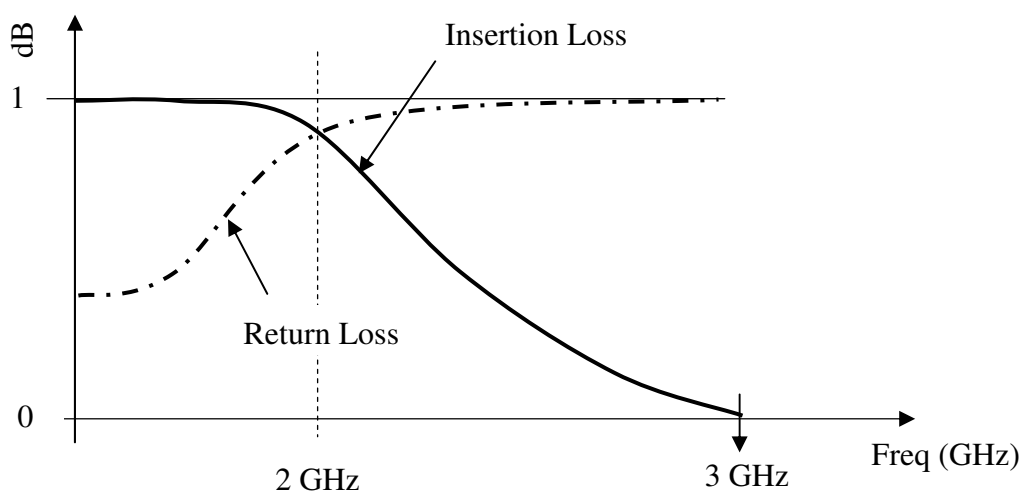


Fig. 2.6: The approximation of return loss and insertion loss in magnitude.

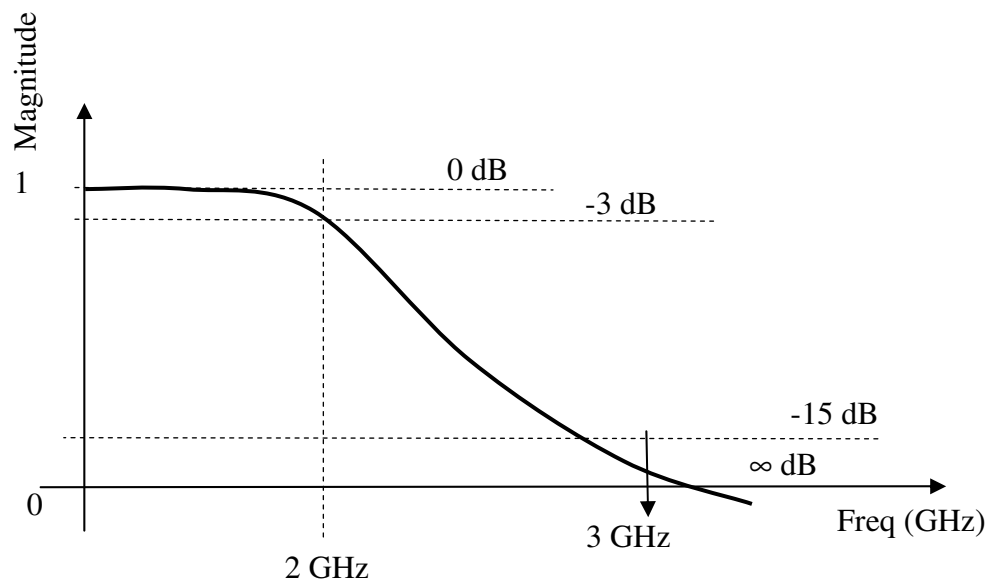


Fig. 2.7: The Insertion Loss responses.

**CHAPTER 3:**  
**MICROWAVE FILTERS DESIGN PROCEDURE**  
**(LOW PASS FILTER)**

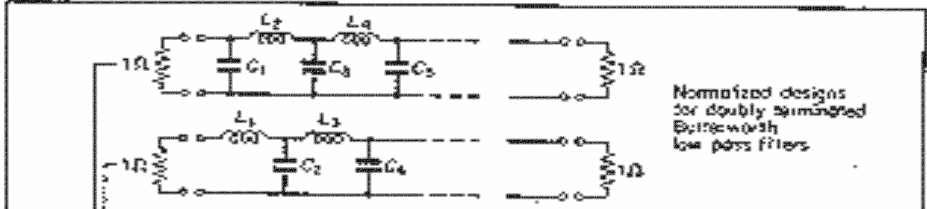
### 3.1 THE FIVE ELEMENTS MAXIMALLY-FLAT (BUTTERWORTH) LOW-PASS FILTER

The 5-elements maximally (Butterworth) flat low-pass filter with

$$f_c = 2 \text{ GHz}$$

$$\epsilon_r = 2.33 \text{ with thickness } 0.5\text{mm of 'Duroid 5870'}$$

Design data in normalised form of Butterworth Low-pass filters [5,7].



n number of elements	C <sub>1</sub>	L <sub>2</sub>	C <sub>3</sub>	L <sub>4</sub>	C <sub>5</sub>	L <sub>6</sub>	C <sub>7</sub>	L <sub>8</sub>	C <sub>9</sub>	L <sub>10</sub>
1	2.000									

<b>5</b>	<b>0.618</b>	<b>1.618</b>	<b>2.000</b>	<b>1.618</b>	<b>0.618</b>					
4	0.7054	1.848	1.848	0.7054						
5	0.6180	1.618	2.000	1.618	0.6180					
6	0.5178	1.414	1.932	1.932	1.414	0.5178				
7	0.4450	1.247	1.802	2.000	1.802	1.247	0.4450			
8	0.3902	1.111	1.653	1.902	1.902	1.653	1.111	0.3902		
9	0.3473	1.000	1.532	1.879	2.000	1.879	1.532	1.000	0.3473	
10	0.3129	0.9000	1.414	1.782	1.975	1.975	1.782	1.414	0.9000	0.3129

Table 3.1: Design data in normalised form for Butterworth Low-pass Filters.

By referring to the design data of Butterworth low-pass filter in Table 3.1, the Butterworth prototype filter will be realised. The filter prototype shows in Fig. 3.1.



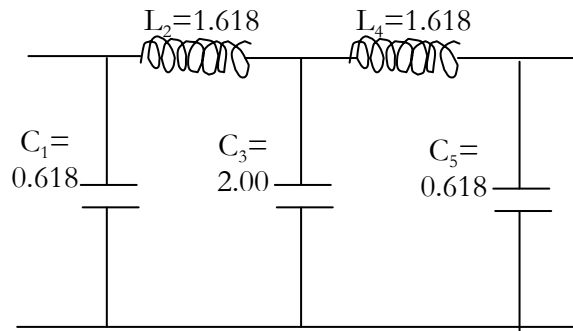


Figure 3.1: Five-Element Prototype Butterworth low-pass filter.

The prototype values also called the normalised values, the normalised value then changed into the actual value by denormalised the value of prototype [3].

Element	Normalise Element Value
$C_1$ (Capacitor 1)	<b>0.618</b>
$L_2$ (Inductor 2)	<b>1.618</b>
$C_3$ (Capacitor 3)	<b>2.000</b>
$L_4$ (Inductor 4)	<b>1.618</b>
$C_5$ (Capacitor 5)	<b>0.618</b>

Table 3.2: Lumped prototype values

And the values of denormalising should be multiply C elements by  $1/(Z_0\omega_c)$ , and L elements by  $Z_0/\omega_c$  by taking  $Z_0$  is  $50\Omega$ , and

$$\begin{aligned}\omega_c &= 2\pi (2 \times 10^9) \\ &= \underline{4\pi \times 10^9}\end{aligned}$$

where,

$Z_0$  is value of source and load termination and

$f_c$  the value of cut-off frequency (2 GHz).

And the actual values after denormalisation are;

$$\begin{aligned} C_1 &= 0.618 \times 1/(50\Omega)(4\pi \times 10^9) \\ &= \underline{\underline{0.9836 \text{ pF}}} \end{aligned}$$

$$\begin{aligned} C_3 &= 2.000 \times 1/(50\Omega)(4\pi \times 10^9) \\ &= \underline{\underline{3.1831 \text{ pF}}} \end{aligned}$$

$$C_5 = \underline{\underline{0.9836 \text{ pF}}}$$

$$\begin{aligned} L_2 &= 1.618 \times (50\Omega)/(4\pi \times 10^9) \\ &= \underline{\underline{6.4378 \text{ nH}}} \end{aligned}$$

$$\begin{aligned} L_4 &= 1.618 \times (50)/(4\pi \times 10^9) \\ &= \underline{\underline{6.4378 \text{ nH}}} \end{aligned}$$

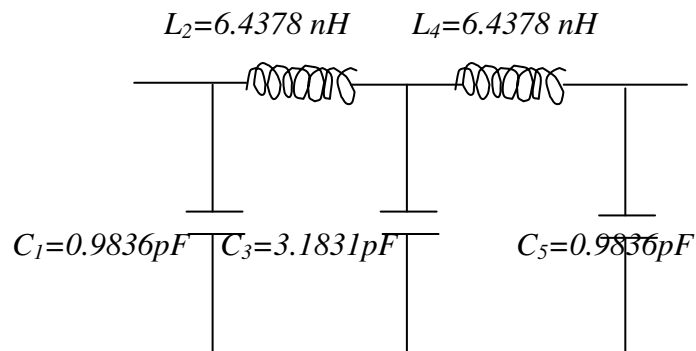


Figure 3.2: The lumped element circuit of Butterworth Low-pass filter.

Element	Normalised Element Value	Actual Element Value
$C_1$ (Capacitor 1)	0.618	<b>0.9836 pF</b>
$L_2$ (Inductance 2)	1.618	<b>6.4378 nH</b>
$C_3$ (Capacitor 3)	2.000	<b>3.1831 pF</b>
$L_4$ (Inductance 4)	1.618	<b>6.4378 nH</b>
$C_5$ (Capacitor 5)	0.618	<b>0.9836 pF</b>

Table 3.3: Actual values of elements

## 3.2 TRANSFORMATION LUMPED TO DISTRIBUTED ELEMENTS

### 3.2.1 The values of Low Impedance ( $Z_L = 25\Omega$ ).

#### 3.2.1.1 Capacitances

$$\lambda_o = \frac{(3 \times 10^8)}{(2 \times 10^9)} = 0.15m$$

$$\omega_c = 2\pi f_c = 12.566 \times 10^9$$

where  $\lambda_o$  is open air wavelength and  $c$  is a velocity of light ( $3 \times 10^8$ ).

By using lineCal module in Eesof HP Touchstone, the value of  $k$  (effective) which is the value of effective relative permittivity ( $\epsilon_{re}$ ) of capacitance's, 2.09. (Appendix A)

$$\epsilon_{re} = 2.09 \quad ; \quad Z_L = 25 \Omega$$

$$\lambda_L = \frac{\lambda_o}{\sqrt{\epsilon_{re}}} = \frac{0.15}{\sqrt{2.09}} = 0.104m$$

where,  $Z_L$  is the lowest realisable characteristic impedance (usually 25  $\Omega$ ) and  $\lambda_L$  is the wavelength for a low impedance transmission line value and  $\omega$  is the cut-off frequency of the filter.

**Capacitor 1 ( $C_1 = 0.9836$  pF)**

Length (mm)

$$\begin{aligned}
 l_1 &= \{\lambda_L \omega_c C_1 Z_L\} / 2\pi \\
 &= \{0.104 \times 2\pi (2 \times 10^9)(0.9836 \times 10^{-12}) \times 25\Omega\} / 2\pi \\
 &= \mathbf{5.115mm}
 \end{aligned}$$

Electrical length parameter ( $l_e$ )

$$l_e = \{(5.115 \times 10^{-3}) / 0.104\} \times 360^\circ = \mathbf{17.71^\circ}$$

Width (W) = **5.93 mm**

Length (L) = **5.09mm**

**Capacitor 3 ( $C_3 = 3.1831$  pF)**

Length (mm)

$$\begin{aligned}
 l_3 &= \{\lambda_L \omega_c C_3 Z_L\} / 2\pi \\
 &= \{0.104 \times 2\pi (2 \times 10^9)(3.1831 \times 10^{-12}) \times 25\Omega\} / 2\pi \\
 &= \mathbf{16.552mm}
 \end{aligned}$$

Electrical length parameter ( $l_e$ )

$$l_e = \{(16.552 \times 10^{-3}) / 0.104\} \times 360^\circ = \mathbf{57.30^\circ}$$

Width (W) = **5.94 mm**

Length (L) = **16.49mm**

**Capacitor 5 ( $C_5 = 0.9836 \text{ pF}$ )**

**Length (mm)**

$$\begin{aligned}l_1 &= \{\lambda_L \omega_c C_1 Z_L\} / 2\pi \\ &= \{0.104 \times 2\pi (2 \times 10^9)(0.9836 \times 10^{-12}) \times 25\Omega\} / 2\pi \\ &= \mathbf{5.115\text{mm}}\end{aligned}$$

**Electrical length parameter ( $l_e$ )**

$$l_e = \{(5.115 \times 10^{-3}) / 0.104\} \times 360^\circ = \mathbf{17.71^\circ}$$

$$\text{Width (W)} = \mathbf{\underline{5.93 \text{ mm}}}$$

$$\text{Length (L)} = \mathbf{\underline{5.09\text{mm}}}$$

*Note:*

The values of width (W) and length (L) taken from the LineCal module, when

physical and electrical length values were keyed.

### **3.2.2 The Values of High Impedances ( $Z_H = 90 \Omega$ )**

#### **3.2.2.1 Inductances**

$$\begin{aligned}\lambda_o &= (3 \times 10^8) / (2 \times 10^9) \\ &= \mathbf{\underline{0.15\text{m}}} \\ \omega_c &= 2\pi f_c = 12.566 \times 10^9\end{aligned}$$

where  $\lambda_o$  is open air wavelength and  $c$  is a velocity of light ( $3 \times 10^8$ ).

Same as capacitors, using lineCal in Eesof HP Touchstone, the value of  $k$  (effective) which is the value of effective relative permittivity ( $\epsilon_{re}$ ) of inductances, 1.85.

(See Appendix B)

$$\epsilon_{re} = 1.85 \quad ; \quad Z_H = 90 \Omega$$

$$\begin{aligned} \lambda_H &= \lambda_0 / \sqrt{\epsilon_{re}} = 0.15 / \sqrt{1.85} \\ &= \underline{0.110m} \end{aligned}$$

where,  $Z_H$  is the highest realisable characteristic impedance (usually taken as 130  $\Omega$ ),  $\lambda_H$  is the wavelength for a high impedance transmission line, and  $\omega$  is the cut-off frequency of the filter.

**Inductor 2 ( $L_2 = 6.4378 \text{ nH}$ )**

**Length (mm)**

$$\begin{aligned} L_2 &= \{ \lambda_H \omega_c L_2 \} / 2 \pi Z_H \\ &= \{ 0.110 \times 2\pi (2 \times 10^9) (6.4378 \times 10^{-9}) \} / 90 \Omega (2\pi) \\ &= \mathbf{15.736mm} \end{aligned}$$

**Electrical length parameter ( $l_e$ )**

$$l_e = \{ (15.736 \times 10^{-3}) / 0.110 \} \times 360^\circ = \mathbf{51.50^\circ}$$

Width ( $W$ ) = **0.813 mm**

Length ( $L$ ) = **15.77mm**

**Inductor 4 ( $L_4 = 6.4378 \text{ nH}$ )**

Length (mm)

$$\begin{aligned} L_4 &= \{\lambda_H \omega_c L_4\} / 2\pi Z_H \\ &= \{0.110 \times 2\pi (2 \times 10^9)(6.4378 \times 10^{-9})\} / 90\Omega(2\pi) \\ &= \mathbf{15.736mm} \end{aligned}$$

Electrical length parameter ( $l_e$ )

$$l_e = \{(15.736 \times 10^{-3}) / 0.110\} \times 360^\circ = \mathbf{51.50^\circ}$$

$$\text{Width (W)} = \mathbf{0.813 \text{ mm}}$$

$$\text{Length (L)} = \mathbf{15.77mm}$$

*Note:*

The values of width (W) and length (L) taken from the LineCal module, when physical and electrical length values were keyed.

<b>Element</b>	<b>Normalised Element Value</b>	<b>Actual Element Value</b>	<b>Width (W) mm</b>	<b>Length (L) mm</b>
<b>C<sub>1</sub></b> (Capacitor 1)	0.618	0.9836 pF	5.93	5.09
<b>L<sub>2</sub></b> (Inductance 2)	1.618	6.4378 nH	0.81	15.77
<b>C<sub>3</sub></b> (Capacitor 3)	2.000	3.1831 pF	5.94	16.49
<b>L<sub>4</sub></b> (Inductance 4)	1.618	6.4378 nH	0.81	15.77
<b>C<sub>5</sub></b> (Capacitor 5)	0.618	0.9836 pF	5.93	5.09

Table 3.4: Overall values of microstrip Low-Pass Filter

### 3.2.3 Actual Butterworth Low-Pass Filter

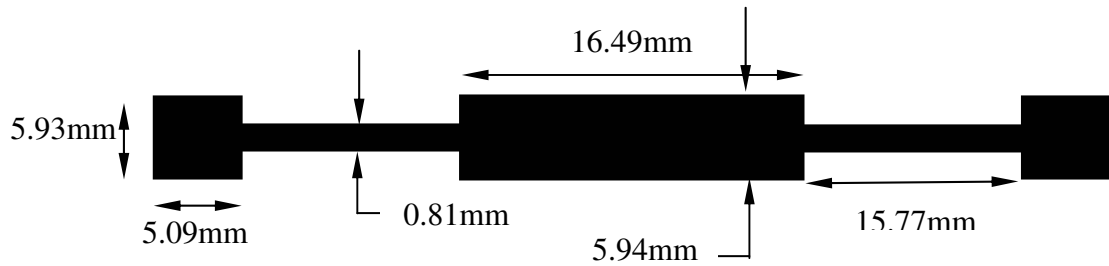


Figure 3.3: The filter layout.

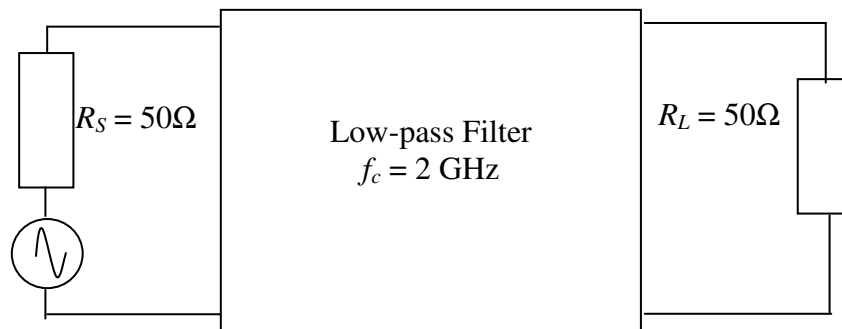


Figure 3.4 shows the low-pass prototype in connecting with generator and its termination ( $R_L$  and  $R_S$ ) [6].



**CHAPTER 4:**  
**FABRICATION TECHNIQUES**

## 4.0 FABRICATION PROCESS OF MICROSTRIP CIRCUIT

### 4.1 Introduction

In modern day most super semiconductors are been processes in mass production, by using high technology machines. Machines are supported by computerise programming to get high precision, high quality and satisfied guarantee of consumers. Designing which is created by computer software becoming a priority among engineer or designer.

CAD is using for microstrip designs. The circuit created using HP Eesof TouchStone Libra after simulation is then converted into TS2ACAD module on TouchStone package. Afterward translate that program into AUTOCAD files in \*.DXF or \*.DXG extension file. That AutoCad file and than exported into VISIO Technical software from which the layout was printed on a transparency to form the mask artwork.

The result of VISIO Technical artwork master is almost always a 1:1 scaled conductor pattern. Most CAD software is capable of producing ‘phototools’ directly. All software can produce a high quality 1:1 scaled positive print (black conductor pattern on white paper) with high-resolution laser printer.

This chapter gives detail explanation about the processes involved in the fabrication of microstrip circuits. The following flow chart shows the actual fabrication process of microstrip,

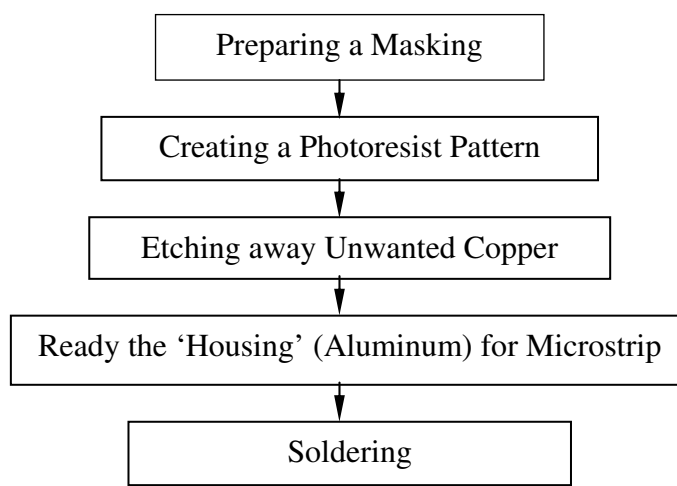


Figure 4.1:

Flowchart of fabrication processes.

#### 4.2 Preparing a masking

Mask or transparency is the layout of artwork master that resulted from TouchStone (CAD software) in a scaled conductor pattern. TouchStone is powerful software, has a capability to create exactly pattern with aids from TS2ACAD module program, the .CKT file is then translated into TS2ACAD and having AutoCAD filed called .DXF (i.e. LPF.DXF). This file can be read out by AutoCad software. Actually, AutoCAD is interchange software to come out with VISIO Technical file and then printed out on transparency, the master of layout is on shaded image.

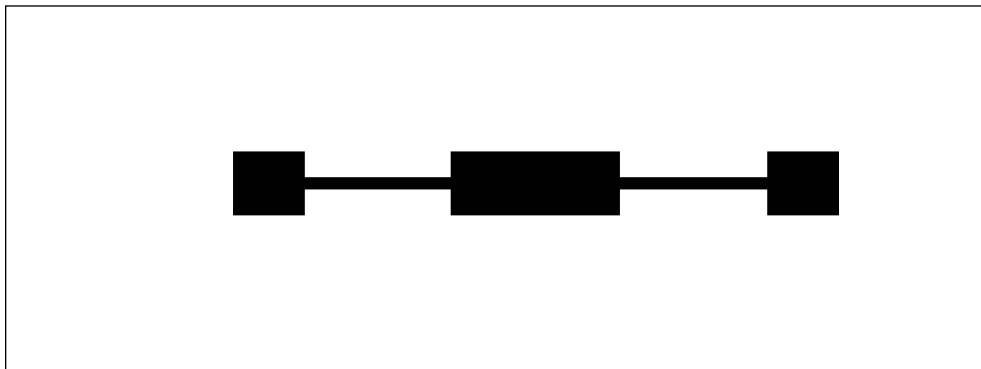


Figure 4.2: The Microstrip layout

Why we use VISIO Technical here? AutoCAD software doesn't has a probability to print out with 1:1 scale. Because of this reason VISIO Technical take a placed.

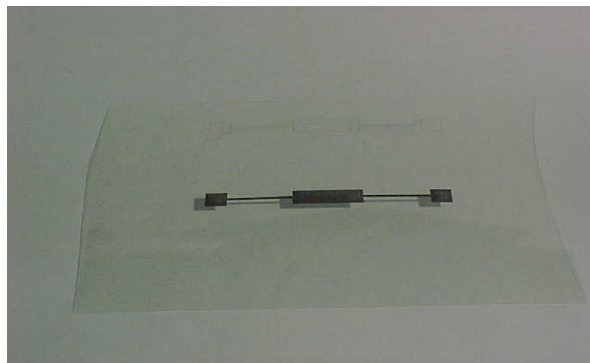


Figure 4.3: The mask

### 4.3 VISIO Technical

The main reason is to use the VISIO is that a 1:1 scaled layout can be produced and can be printed out. Since the microstrip is miniature in structure, the viewing can be enlarged above 100% and this factor can really help designers to check it out the accuracy of the microstrip layout.

In VISIO Technical,

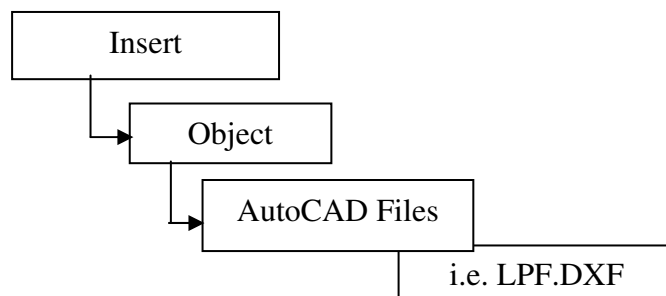


Figure 4.3: VISIO Technical to call AutoCAD files.

The .DXF file produced by the AutoCAD program is not in scaled after transferred into .VSD (VISIO Technical file) and then adjust to filling with the black shading. Using high-resolution Laser jet printer then prints the scaled-layout.

Masking is ready on transparency type as output from LaserJet printer. Now, the mask is ready to used and proceeds for photoresist.

### 4.4 Photoresist Process.

The filter was realised using normal Printed Circuit Boards (PCB) procedure.

#### **4.4.1 Photoresist Material**

The following are required to create layout circuit on the photoresist:

- i. Plastic tray
- ii. Photoresist Solution
  - Photoresist Positive (Spray type)
  - Photoresist Developer (Liquid)

\*Note: Both Positive & Developer are usually purchased together.

- iii. Lid water ('Battery water' are recommended)

#### **\*ATTENTION:**

Developer and Positive photoresist must handle with care, avoid contact with skin and eyes and avoid breathing vapour directly. If skin contact occurs, wash with flush water immediately.

#### **4.4.2 Photoresist Equipments**

- i. Ultraviolet Light Compartment.
- ii. Hot Plate with temperature controlled.

#### **\*ATTENTION:**

Do not directly eyes expose to the Ultraviolet lights.

#### **4.4.3 Steps of the photoresist processes.**

The following are shows the steps of photoresist process,

(Each step should be followed carefully. Please keep in mind, two solution has been used).

#### 4.4.3.1 Preparation of Developer Photoresist

Firstly, ready the Photoresist Developer and Lid water with 1:4 in the plastic tray. Prepare for only one microstrip.



Figure 4.4: Positive and Developer Photoresist



Figure 4.5: Ultraviolet exposure

#### 4.4.3.2 Photoresist procedures

##### *Step 1.*

Peel off the thin film covered on main surface.

(A Microstrip material has a double-sided surface).

- Cleanliness is most important to ensure the piece of microstrip no dust or no oily surface or contaminated surface.
  - The microstrip material was cleaned by 'acetone' about 2~3 minutes. This is to clean dirt or oily contamination on the substrate surface.
  - Almost solution are used such as Trichloroethylene, acetone and Methanol.

##### *Step 2.*

Using a hot plate to warming up the microstrip material. Adjust the hot plate about 100°C. Keep microstrip material on the hot plate about 10 minutes.

##### *Step 3.*

Using Positive Photoresist, spray it on the microstrip material constantly.

- Under 'red safelight', microstrip material is sprayed by Positive Photoresist while it was laid flat on the table. Ensure the sprayed angle about 30° to the workpiece. Gives about 10cm away from the microstrip material.
  - Do not apply too much, because this will trap unwanted bubbles and create uneven images at the develop processing. Also creating the dirty spots after etching process.
- To making a good results of spraying, a photoresist spinner is preferable to eliminates bubbling and ensure the thickness uniformity.

*Step 4.*

Again keep on the hot plate about 5~7 minutes.

(Prepare the Ultraviolet light compartment, turn-on the main switch and set-up the exposure time about 3 minutes).

- Keeping hot gives annealing to the photoresist for increasing its adhesion.

*Step 5.*

Place the mask (transparency) on the compartment glasses; place the main surface into the mask.

- The mask was placed on the glasses in the ultraviolet light source compartment.
- The microstrip material was put on the mask with sensitised surface facing towards glasses.

Position it carefully, to get a good image. Close the compartment by clip-on.

Push on the light and wait until the light off, (light off means the exposure time is finished)

- 3 minutes is the optimum time for the exposure processing. If microstrip substrate is over exposed, diffraction of light will give the poor edge resolution of the image.

\*WARNING:

Looking directly into the ultraviolet source will be damaging your eyes.

*Step 6.*

Remain under red safelight, take out from the compartment and solve with Photoresist Developer solution.

- To remove the unwanted areas which are not ultraviolet exposed and bring out the latent images of the filter.
- The developer photoresist is to be used diluted with distilled water (recommended) at the ratio of 1:4.



Keep on about 5~6 minutes; actually the black images will appear within 2~4 minutes.

#### **4.4.4 Etching process**

The etching was realised using a normal Printed Circuit Board (PCB) etching procedures.

Etching is the process of removing unprotected copper from the microstrip to yield the wanted copper as conductor pattern. The common solution are used by industries are Ammonium Persulfate, Chromic Acid, Cupric Chloride and Ferric Chloride.

The better solution used since it is relatively safe are Ferric Chloride, it is readily available at costs moderate hence produces excellent results.

This etching procedure is probably the easiest method. The etching container is filled with acid to a depth that will cover the submerged microstrip. The concentration of Ferric Chloride is not environment friendly, be careful when under processing.

##### **4.4.4.1 The concentration of solution**

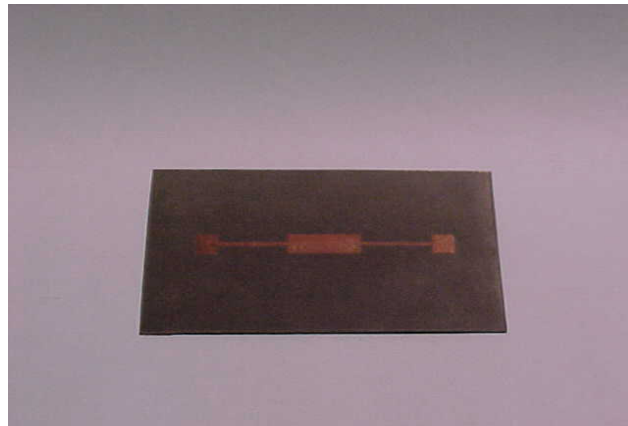
The inside temperature with filled container is kept constant at 50°~55° C by keep on the heater. The concentrations are constantly agitating with the built in air pump at the container.

There are three factors identified affected to the strength of concentration during etching process:

- i. The solution aged
- ii. Agitated concentration
- iii. Temperature of the concentration

Ferric Chloride should be used over and over again, but each time a microstrip circuit is etched, copper is removed and acid will be less strengthen or diluted. Less

strengthens of concentration gives a more times to solve it. For the better result for microstrip processing, the new concentrations were used. It takes approximately one hour to etch a small piece of microstrip. The agitating and temperature also take place to speed up the etching process. More agitating and with suggested temperature would cut more time to finish it. Every time to time microstrip circuit has been checked. Satisfied microstrip, when unwanted copper is removed. The microstrip circuit was



thoroughly rinsed under running water to avoid the chemical reaction. And the board will be handle with bare hands and should be proceed to further processing.

Figure 4.6: The Microstrip Circuit.

#### 4.4.5 Microstrip Housing (Ground Plane)

There is two types of materials are using for a microstrip base or ground plane.

- Copper and
- Aluminium

These materials are good conductors, the fields will be confined very properly and easy to work at any condition. This project are used Aluminium as a base of microstrip, it is light then copper.

To maintain with accurate touch with the base, tightly screwed must done at four corner of microstrip. The locations of SMA connectors are properly drilled at the side of Aluminium. The finishing part is to make it smooth and shiny surfaces and form a good craftsmanship.

More careful when drilling the holes for SMA connectors ensure by properly aligned.

#### **4.4.6 Soldering the Terminal Connector**

Once the SMA connector are tightly screwed into the aluminium base, the launchers of the SMA connectors are soldered into microstrip circuit. Ensure that soldering process is neatly done to avoid effect of resonance on the circuit. The continuity testing using a multimeter to ensure connection between SMA connector and microstrip are properly done.

After all above are completely satisfied, the Low-Pass filter is readied to measured and characterised.

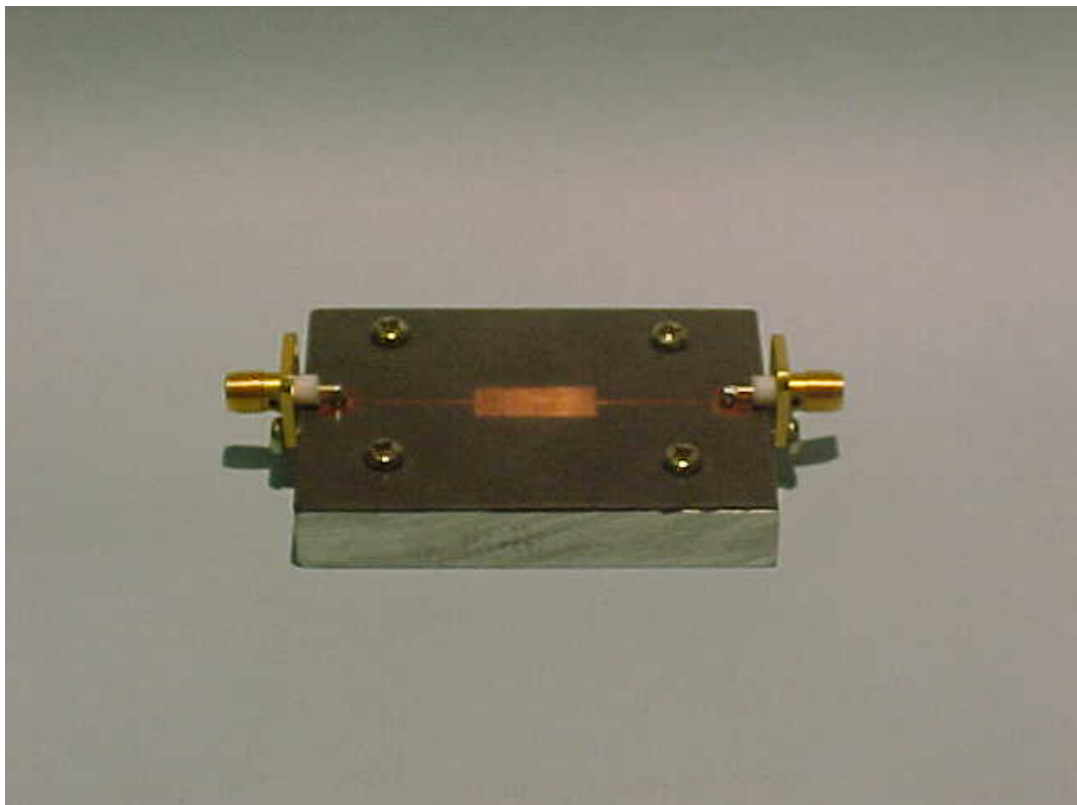


Figure 4.7: Low-Pass Filter ( Zulkifli Mohd Sidi ©)

## **CHAPTER 5**

### **MEASUREMENTS AND TESTING**

## 5.1 Introduction

In very high frequency especially microwave frequency, the two-port networks are better to measured in terms of scattering parameters (S-parameter). S-parameter are defined in terms of travelling waves, it is natural variables to be used in transmission line [6].

### 5.1.1 Why we used S-parameters

There is a lot parameters or description such as  $Z$ - Matrix,  $Y$ -Matrix and  $h$ -Parameters but these parameters are not suitable for microwave frequencies measurement.

The reasons are:

- There is *no equipment* available to measure total voltage and total current at the microwave frequencies. It is meaningful to analyse microwave circuits in terms of travelling wave components,  
(i.e.  $V = V_i e^{j\beta l} + V_r e^{-j\beta l}$ ) - The summing of incident and reflected travelling voltages.
- The fringing field associated with an open circuit, these are *not easily obtained* when open circuit and short circuit termination required determining the matrix elements.
- Active devices may become *unstable* under open and short circuit condition may damage or burn those devices.
- Transistor models *not truly represent* actual device character and no equivalent circuit is needed for S-parameter.

### 5.1.2 The Definition Equation of S-Parameter

The values of the S-parameters for a network depend upon the choice for the positions of the reference plane. Since we know the reference plane, it will be easy to measure, analyse the DUT and calibration the measurement tools such as Scalar Network Analyser become simple.

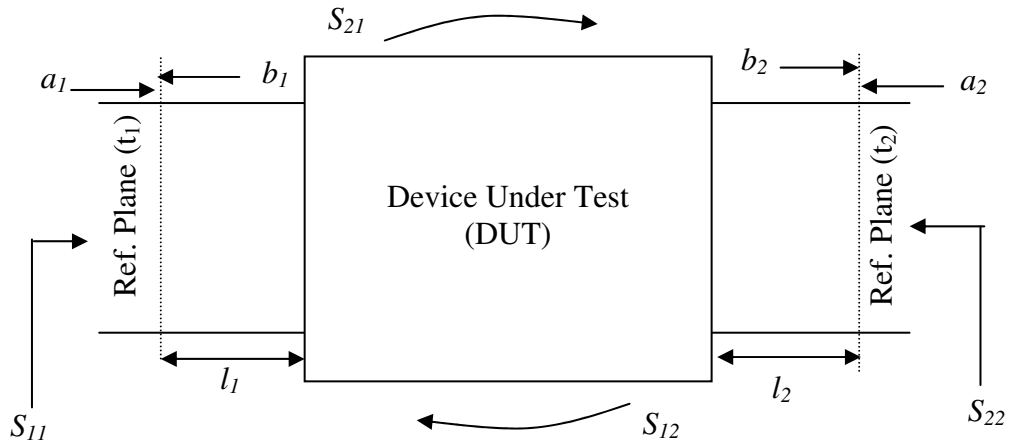


Figure 5.1: Normalised-travelling voltage waves for two-port network.

Reference plane ( $t_1$  and  $t_2$ ) play important role to measure S-parameters

The definition equations of S-parameters are:

$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2$$

If matched load is connected at  $t_2$  with an input at  $t_1$  only, then  $a_2 = 0$ , therefore

$$S_{11} = b_1/a_1 \quad - \quad \text{input reflection coefficient at } t_1$$

$$S_{21} = b_2/a_1 \quad - \quad \text{voltage transfer ratio from } t_1 \text{ to } t_2.$$

Similarly, if a matched load is connected at  $t_1$  with an input applied at  $t_2$ ,  $a_1 = 0$ .

$S_{22} = b_2/a_2$  - reflection coefficient at  $t_2$ .

$S_{12} = b_1/a_2$  - voltage transfer ratio from  $t_2$  to  $t_1$ .

### 5.1.1 Equipments

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## Microwave Formulas

### Dispersion in Microstrip

$$\begin{aligned} f'_c &= 0.3 [ Z_0 / (h \sqrt{\epsilon_r - 1}) ] \text{ GHz.} \\ \epsilon_{re} &= \epsilon_r - \{ [ \epsilon_r - \epsilon_{re} ] / [ (0.6 + 0.009 Z_0) (8\pi h f / Z_0)^2 ] \} \end{aligned}$$

Where, h is centimeter (cm) ,  
f is frequency (GHz)  
Z<sub>0</sub> is impedances.

$$\begin{aligned} \text{Return Loss (RL)} &= -20 \text{ Log}_{10} |\Gamma| \text{ dB} \quad \text{or} \\ &= -20 \text{ Log}_{10} 1 / |S_{21}|^2 \text{ dB} \end{aligned}$$

### Conductor Loss

$$\alpha_c =$$