DESIGN MULTILAYER BANDPASS FILTER USING HAIRPIN RESONATOR
FOR DIGITAL BROADCASTING

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CHAPTER 1

INTRODUCTION

1.1 Introduction

TV can be broadcast by satellite, terrestrially or through cable. These three delivery methods have been for many years using analogue transmission. Recently, TV broadcasting is now undergoing a revolutionary change to digital broadcasting. Many countries worldwide including Malaysia are already using Digital Broadcasting by satellite. Satellite television like other communication relayed by satellite starts with a transmitting antenna located at an uplink facility and finally received radio wave from satellite transponder at downlink facility [1] . Nonlinear circuit in satellite broadcasting system such as mixer and amplifier usually generate unwanted frequency components in additional to amplified desired signal. The unwanted frequency components are usually harmonic components, image signal and intermodulation distortion components, which will degrade the integrity of the desired signals.

In recent years, the demand for small-size and high performance microwave filters is growing rapidly in various communication systems. Conventional design theory and circuitry of microwave filters are meeting new and exciting challenges in realizing unprecedented demands and applications [2]. Filtering technology is still focusing on how to operate in higher performance requirement, smaller size, lighter weight and lower cost. In order to meet these requirements, several types of planar micro strip filters, such as resonator filters, open loop resonator filters, and stepped impedance resonator filters have been proposed. However, a planar micro strip filters are implemented on a single micro strip substrate layer which takes often a large size. Therefore to overcome this problem there has recently been increasing interest in multilayer band pass filters. The design using multilayer structure approach has been proposed for reducing the size and increasing the bandwidth of the micro -strip filters.

1.2 Problem statement

The demand for new technologies required high performance and more compact electronic components in such devices. Filters are one of the electronic components essential in such system to operate in high efficiency. The design of single-layer filter using symmetric couple microstrip lines is well documented in literature. However, tight coupling lines between the resonators in this configuration are difficult for the fabrication to be realized. Multilayer filter overcome this kind of restriction by producing flexible coupling between adjacent resonators on same or different layers therefore miniaturize filter can be realized.

Hairpin-line provides compact structures in the filter design. They can conceptually be obtained by folding the resonators of parallel-coupled half wavelength resonator into a "U" shape. However, to fold the resonators, it is necessary to take into account the reduction of the coupled-line lengths, which reduces the coupling between resonators. If the two arms of each hairpin resonator are closely spaced, it will act as a pair of coupled line which can affect the coupling as well. Thus, several optimizations must be carefully done to avoid this kind of problem that can affect the overall response. This research will contribute towards a small size filter using the latest multilayer stack up model for digital broadcasting application.

1.3 Objectives:

The Main objectives of this research are:

- To design and fabricate a microstrip parallel coupled line band pass filter at ceneter frequency 2.58 GHz .
- To design a microstrip multilayer hairpin band -pass filter with a compact in size at 2.58 GHz .
- To analyze the effects of using different substrate materials between RO3003 and FR4 for parallel coupled line and multilayer hairpin band pass filter .

1.4 Scope

The scopes of this project is focus on a compact design of band pass filters using 4-poles resonantors where resonant frequency of the filters are selected as 2.58 GHz . the filters are simulated using Advanced Design System (ADS) and Computer Software Technology (CST) .The proposed design filter is fabricated and tested using Network analyzer. The responses of the filters are analyzed and the optimization process are perform for the desired response .Figure 1.1 shows the research scope where the bold lines represent the device or configuration are chosen to achieve the aims and objectives and the dotted lins represent other devices or configuration which are not discussed in this thesis.

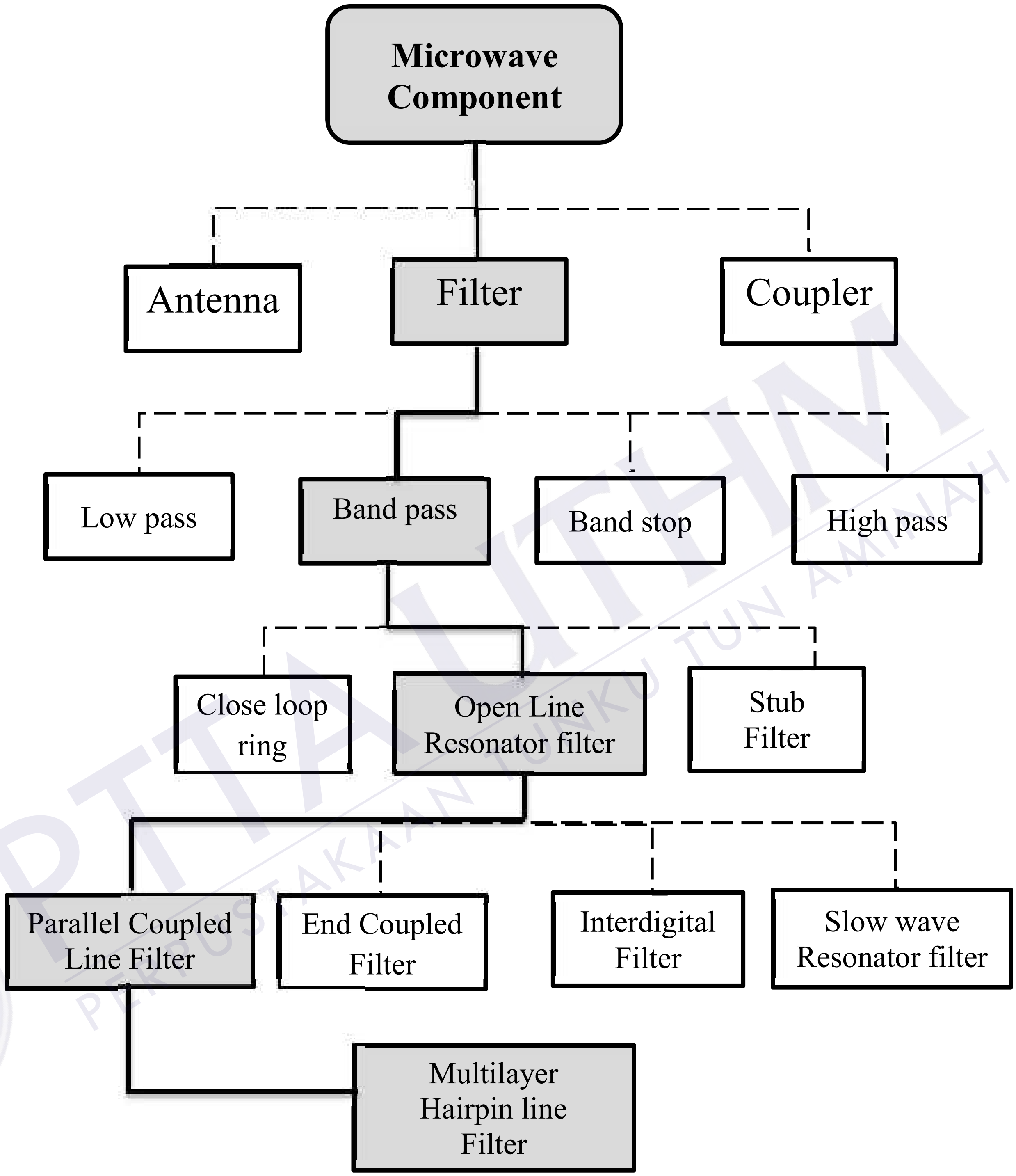

Figure 1.1: Research scope

1.5 Thesis Outline

Chapter 1 provides an overview of the project design. It covers the introduction to digital broadcasting and filter concepts, problem statement, objectives, significant and the scope of work in this project.

Chapter 2 focuses on the literature review about the basic concepts of filter design. These include reviewing on multilayer filter, structure used and computer aided design (CAD) in details.

Chapter 3 discuss the methodology of designing the paraell coupled line and multilayer hairpin band-pass filter which include the design flowchart, specification and the method of determining the physical layout of the filter.

Chapter 4 presents the results obtained from the simulation process and discussed the effect on varying filter parameters the filter response and measurement result .

Chapter 5 briefly concludes the whole project including future improvement and development that can be made .

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Microwave filter is a two-port component (network) used to provide frequency selectivity in satellite and mobile communications, radar, electronic warfare, metrology, and remote-sensing systems operating at microwave frequencies (1GHz) and above [6] . Microwave filters perform the same function as electric filters at lower frequencies, but differ in their implementation because circuit dimensions are on the order of the electrical wavelength at microwave frequencies. Thus, in the microwave regime, distributed circuit elements such as transmission lines must be used in place of the lumped-element inductors and capacitors used at lower frequencies. The use of microstrip in the design of microwave components and integrated circuits has gained tremendous popularity since the last decades because microstrips can operate in a wide range of frequencies. Furthermore, microstrip is lightweight, easier fabrication, integration, and cost effective. Many researchers have presented numerous equations for the analysis and synthesis of microstrip. However, along with the sophistication comes with a high price tag, copy protection schemes and training requirements that create difficulties for exploratory usage in an academic environment.

2.2 Filter

A microwave filter is a two-port network used to control the frequency response at a certain point in a microwave system by providing transmission at frequencies within the pass-band of the filter and attenuation in the stop-band of the filter [6] . Filters may be classified in a number of ways. An example of one such classification is reflective versus dissipative. In a reflective filter, signal rejection is achieved by reflecting the incident power, while dissipative filters are used in most applications. The most conventional description of a filter is by its frequency characteristic such as low-pass, high-pass, band-pass or band-reject (notch).

2.2.1 Basic FilterTypes

In microwave communications, there are mainly five types of filter used which are briefly described in the following [4] . The frequency range of the filter as shown in Figure 2.1.

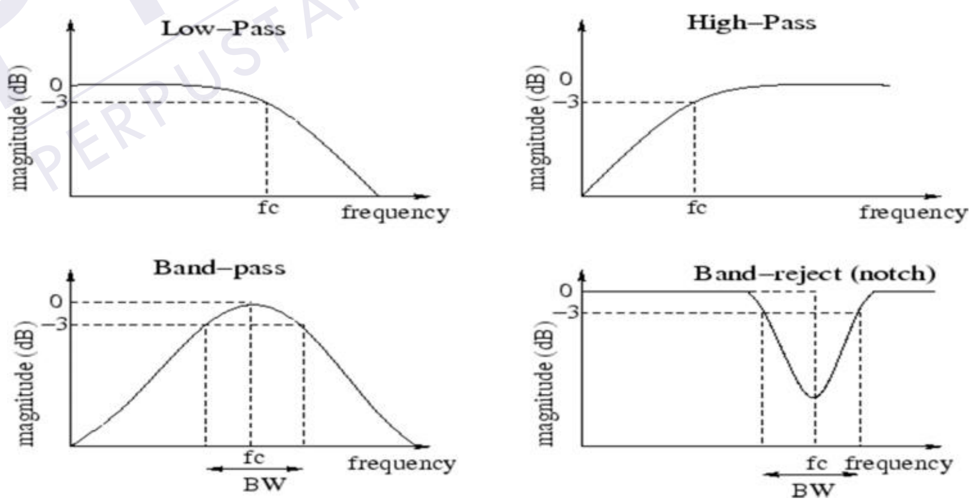

Figure 2.1: Amplitude response of different filter types [4]

2.2.1.1 Low-Pass Filter

Low-pass filter networks transmit all signals between DC and some upper limit w_C, and attenuate all signals with frequencies above cut-off frequency. They are realized using a cascade of series inductors and shunt capacitors.

2.2.1.2 Band-Pass Filter

The band-pass filter shows the signal is transferred to the load in a band of frequen- cies between the lower cut-off frequency and the upper cut-off frequency between the lower and upper cut-off frequency is the centre frequency , defined by the geometric mean of lower cut-off frequency and upper cut-off frequency . A band-pass filter will pass a band of frequencies while attenuating frequencies above or below that band. In this case the passband exists between the lower passband edge frequency and the upper passband edge frequency.

2.2.1.3 Band-Reject (Stop) Filter

The band-reject filter is a complement of the band-pass filter. The signal experiences high loss between upper cut-off frequency and lower cut-off frequency , hence the name band-stop or band-reject. In this case the band of frequencies being rejected is located between the two pass-bands. The stop-band exists between the lower stop-band edge frequency and the upper stop-band edge frequency.

2.2.1.4 All-Pass Filter

The all-pass filter allows the signal amplitude for all frequencies to pass through the network without any significant loss. This network has no frequency selective pass band or stop band.Typically frequency and amplitude responses for these difference types are shown in Figure 2.1. In additional, an ideal filter displays zero insertion loss, constant group delay over the desire pass-band and infinite rejection elsewhere. However, in practical filters deviate from these characteristics and the parameters in the introduction above are a good measured of performance as shown in Figure 2.1.

2.2.2 Applications of Filters

As mentioned above, virtually all microwave receivers, transmitters and etc are typically commonly used circuits that require filters include mixers, transmitters and multiplexers. Multiplexers are essential for channelized receivers. Therefore, system application of filters including radar, communications, surveillance, EMS receiver, Satellite Communication (SATCOM), mobile Communication , direct broadcast, satellite systems, personal communication system (PCS) and microwave FM multiplexer. In many instances, such as PCS, miniature filter are a key to realizing require reduction in size. There is, however, a significant reduction in power handling capacity and an increase in the insertion loss. The former is not a severe limitation in such system, however, and the latter can be compensated for by subsequent power application.

2.2.3 Filter Classifications by Response Type

Based on designing signal processing filters, there are several important classes of filter such as Butterworth filter, Chebyshev filter, Elliptic (Cauer) filter, Bessel filter, Gaussian filter, Optimum "L" (Legendre) filter, Linkwitz-Riley filter. It was originally intended to be applied to the design of passive linear analogue filters but its results can also be applied to implementations in active filters and digital filters. The class of a filter refers to the class of polynomials from which the filter is mathematically derived. The order of the filter is the number of filter elements present in the filter’s ladder implementation. Generally speaking, the higher the order of the filter, the steeper the cut-off transition between passband and stop- band. In the following some of filters are described shortly.

2.2.3.1 Butterworth Filter

The Butterworth filter has essentially flat amplitude versus frequency response up to the cut-off frequency. Butterworth filters are also known as maximally flat type filters and have the flattest possible pass-band magnitude response. This class of filters approximates the ideal filter well in the pass band. It has a monotonic decrease in gain with frequency in the cut-off region and a maximally flat response below cut- off. Attenuation is -3dB.

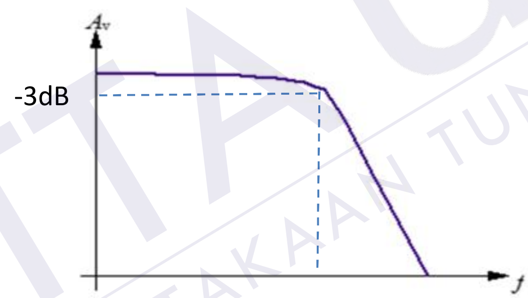

Figure 2.2: Butterworth Filter Response [4]

The pulse response of the Butterworth filter has moderate overshoot and ringing. The Butterworth filter has characteristic somewhere between Chebychev and Bessel filter.

2.2.3.2 Chebychev Filter

The Chebychev filter, also called the equal ripple filter, gives a shaper cut-off than the Butterworth filter in the pass-band. Both Butterworth and Chebychev filters exhibit large phase shift near the cutoff frequency. This filter response has the steeper initial rate of attenuation beyond the cut-off frequency than Butterworth. This advantage comes at the penalty of amplitude variation (ripple) in the pass- band. Unlike Butterworth and Bessel response, which have 3 dB attenuation at the cut-off frequency, Chebychev cut-off frequency is defined as the frequency at which the response falls below the ripple band. For even-order filters, all ripples are above the dc-normalized pass-band gain response, therefore cut-off is at 0 dB. For odd-order filters, all ripple is below the dc-normalized pass-band gain response, so cut-off is at - (ripple) dB . The Chebychev has more ringing in its pulse response than the Butterworth - especially for high-ripple designs.

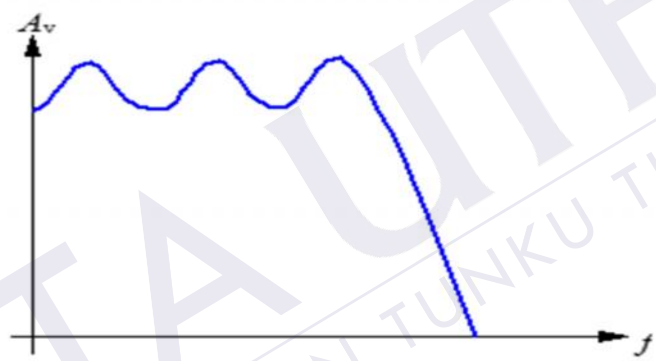

Figure 2.3 : Butterwoth Filter Response [4]

2.3 Microstrip

Microstrip line is one of the most popular types of planar transmission lines widely used in microwave electronic and communication applications. It can be fabricated using photolithographic process and is easily integrated with other passive and active microwave devices such as antennas, filters, attenuators, mixers and amplifier. When the distance between the source and load ends of a transmission line is a few inches or less, standard coaxial cable transmission lines are impractical because the connectors, terminations and cables themselves are simply too large. Microstrip transmission line provides the connection between these components [14].

Microstrip is simply a flat conductor separated from a ground plane by an insulating dielectric material. The ground plane serves as the circuit common point and must at least 10 times wider than the top conductor. The microstrip is generally either one-quarter or one-half wavelength long at the frequency of operation and equivalent to an unbalanced transmission line.

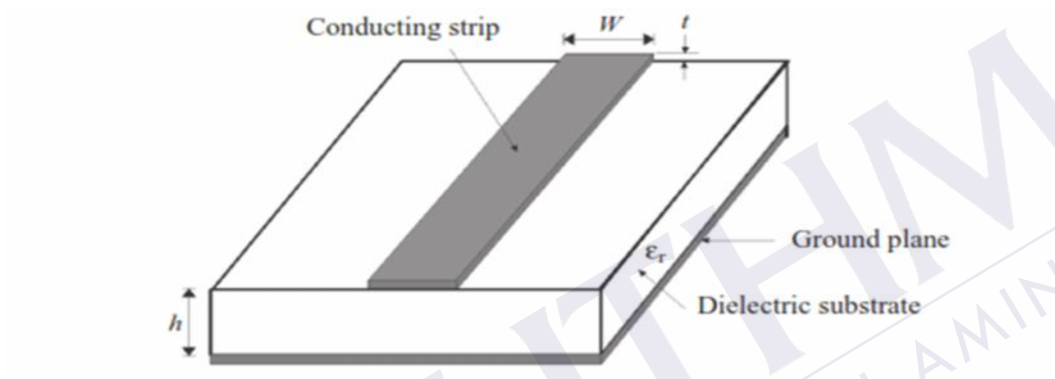

Figure 2.4: Microstrip transmission line structure [14]

As with any transmission line, the characteristic impedance of a microstrip line is dependent on its physical characteristics. Therefore, any characteristic impedance between 50Ω and 200Ω can be achieved with microstrip lines by simply changing its dimensions [9]. The general structure of a microstrip line is shown in Figure 2.4. It has a conducting strip with width, *w* and thickness, *t* on top of the substrate. Each substrate has a relative dielectric constant, ε_r and thickness, *h*. At the bottom of the substrate is the ground plane of thickness, *t*

The equation [9] to calculate the characteristic impedance of an unbalanced microstrip line is:

$$Z_O = \frac{87}{\sqrt{\epsilon + 1.41}} \ln\left(\frac{5.98h}{0.8w + t}\right) \tag{2.1}$$

Where Z_O = characteristic impedance (Ω)

ϵ = dielectric constant (RO3003 ϵ = 3)

w = width of copper trace

t = thickness of copper trace

h = distance between copper trace and ground plane (Dielectric thickness)

2.4 Coupled Microstrip Lines

When two transmission lines are close together, because of the interaction of the electromagnetic fields of each line, power can be coupled between the lines. Those coupled lines are used to construct directional couplers. Generally, in design of directional couplers microstrip and stripline forms are used. Although microstrip transmission lines do not support . It is important that whether true TEM or not, all parallel line couplers have odd and even mode, and resulting Z_{0e} and Z_{0o} (even and odd mode impedances respectively). In the analysis of the directional couplers we will use also even-odd mode analysis. The only difference from Figure 2.4 is that there are two microstrip where s is separation between them , w is the width of resonator , l is the length of resonator and h is the height of substarte as shown in Figure 2.5 [14].

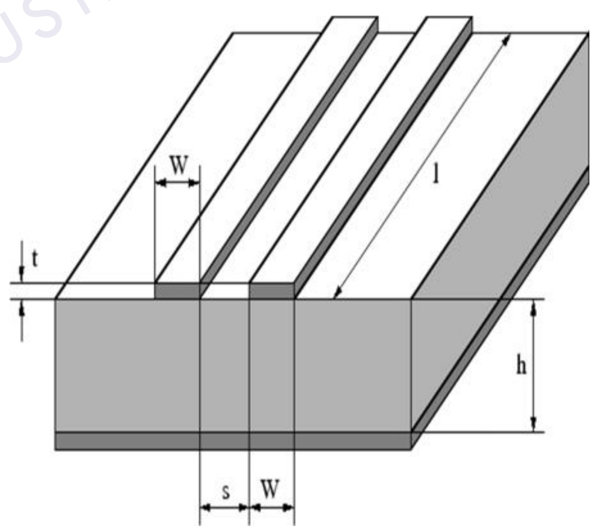

Figure 2.5: Coupled microstrip line [14]

2.5 Quasi-TEM Approximation

Microstrip has quasi–TEM approximation for their wave propagations. When the longitudinal component of the fields for the dominant mode of a microstrip is much smaller than the transverse components, they may be neglected. In a microstrip, the dominant mode then behaves like TEM mode, and the TEM transmission line theory is applicable for the microstrip line as well. This is called the quasi–TEM approximation and it is valid over most of the operating frequency ranges of a microstrip.

Microstrip is inhomogeneous because it extends within two media that is air above and dielectric below. As a result, the microstrip does not support a pure TEM wave. This is because the pure TEM wave are only transverse components, and the propagation velocity depends only on material properties that is permittivity, ε and permeability, μ. However, because of the presence of two different guided wave media, the waves in a microstrip line will have no vanished longitudinal components of electric and magnetic fields. As a result, propagation velocities will depend on material properties and phpysical dimensions of the microstrip. The electric field distribution is shown in Figure 2.6.

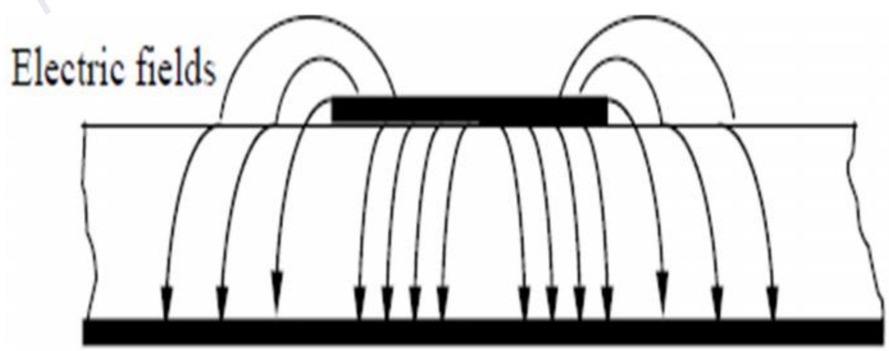

Figure 2.6: Electric field in microstrip [16]

2.5.1 Effective Dielectric Constant and Characteristic Impedance

The transmission characteristic of microstrip can be described by two parameters; effective dielectric constant, ε_{re} and characteristic impedance, Z_o . These parameters can be obtained from quasistatic analysis. It can be written as follows [11] .

$$\varepsilon_{re} = \frac{C_d}{C_a} \tag{2.3}$$

$$Z_o = \frac{1}{c\sqrt{C_a C_d}} \tag{2.4}$$

Where C_d is the capacitance per unit length with the dielectric substrate present , C_a is the capacitance per unit length when the dielectric substrate is air and c is the capacitance. For very thin conductor, more accurate expressions can be obtained as follows [11]:

For W/h ≤ 1,

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\left(1 + 12\frac{h}{W}\right)^{-0.5} + 0.04\left(1 - \frac{W}{h}\right)^2\right] \tag{2.5}$$

$$Z_o = \frac{\eta}{2\pi\sqrt{\varepsilon_{re}}}\ln\left(\frac{8h}{W} + 0.25\frac{W}{h}\right) \tag{2.6}$$

Where, η = 120π is the wave impedance in free space

W = width of substrate

h = thickness of substrate

For W/h ≥ 1,

$$\varepsilon_{re}=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-0.5} \tag{2.7}$$

$$Z_o=\frac{\eta}{\sqrt{\varepsilon_{re}}}\left[\frac{W}{h}+1.393+0.677\ln\left(\frac{W}{h}+1.444\right)\right]^{-1} \tag{2.8}$$

In Figure 2.7 shows the effective dielectric in which t is the thinkness , h the height and W is the width .

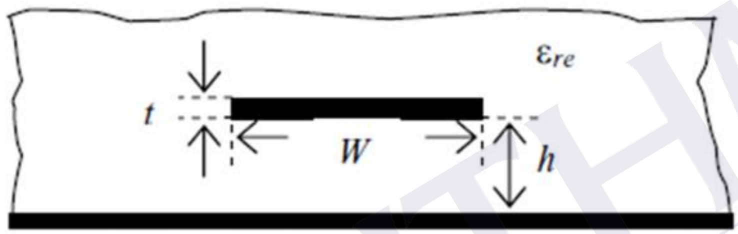

Figure 2.7 : Effective dielectric [17]

Besides the effective dielectric constant and characteristic impedance, there are other important properties in microstrip transmission lines. they are guided wavelength, propagation constant, phase velocity, and electrical length.Once the effective dielectric constant of microstrip is determined the guided wavelength is given by

$$\lambda_g=\frac{\lambda_o}{\sqrt{\varepsilon_{re}}} \tag{2.9}$$

Where, λ_o is the free space wavelength at frequency of operation

The associated Propagation Constant β and phase velocity v_p can be determined

Propagation Constant

$$\beta=\frac{2\pi}{\lambda_g} \tag{2.10}$$

Phase Velocity

$$v_p=\frac{\omega}{\beta}=\frac{c}{\sqrt{\varepsilon_{re}}} \tag{2.11}$$

Where c is the velocity of light in free space and ε_{re} is the effective dielectric.

2.5.2 Substrate Materials

There are two types of substrate materials which is hard and soft substrate. Hard substrate use ceramic, crystalline or semiconductor which is expensive to fabricate and difficult to shape, cut and drill. Soft substrate is available in many range of dielectric constant depending on the material used. The latter is known as Duroid by Rogers Corporation.

Important qualities of the substrate include:

i. The Dielectric constant

ii. The Dielectric loss tangent which sets the Dielectric loss

iii. The thermal expansion and conductivity

iv. The frequency dependence which gives rise to "material dispersion"

v. The surface finish and flatness

vi. The manufacturability (ease of cutting, shaping, and drilling)

High dielectric constant substrate and a slow wave propagation velocity can reduce the radiation loss from the circuit. However at higher frequency, the circuits get smaller which restricts the power handling capability. Characteristic of RO3003 and Characteristic of FR4 are illustrated in Table 2.1and Table 2.2 respectively

Table 2.1: RO3003 Substrate Properties [28]

Parameters	Values
Dielectric constant, ε_r	3
Substrate height, *h*	0.75 mm
Loss tangent, *tan δ*	0.0013
Cooper thickness	0.035 mm

Table 2.2: FR4 Substrate Properties [26]

Parameter	Values
Dielectric constant, ε_r	4.3
Substrate height, *h*	1.6 mm
Loss tangent, *tan δ*	0.021
Cooper thickness	0.035 mm

2.6 Microwave Filter

A microwave filter is a two port network used to control the frequency response at a certain range by providing transmission at frequencies within the pass band and attenuation in the stop band of the filter. Typical frequency responses include low-pass, high-pass, band pass and band stop characteristics. They are many common filter designs which include microstrip, stripline, waveguide and coaxial. The resonator design structures normally used the transmission line consist of combination of multi-lines of at least one quarter wavelength. Using these structures, filters components with different filtering characteristic can be realized. Various design structure for RF/microwave filters are available and most popular include end-coupled, edge-coupled, combine, interdigital, and hairpin structures. Even until today, many researchers are still trying to develop and improve the conventional structures to increase filter performance in technology application. In practice, microwave filters are used extensively over 1 to 40 GHz range where small compact circuits, suitable for the inclusion of active devices and capable of handling up to several watts of power are readily achievable. That frequency range follows the recommendation of IEEE on designations of microwave band tabulated in Table 2.3 .

Table 2.3: IEEE Microwave frequency band [9]

Designation band	Frequency range (GHz)
L band	1.0 – 2.0
S band	2.0 – 4.0
C band	4.0 – 8.0
X band	8.0 – 12.0
Ku band	12.0 – 18.0
K band	18.0 – 27.0
Ka band	– 40.0

2.6.1 Parallel coupled-line bandpass filters

Figure 2.8 illustrates a general structure of parallel coupled-line microstrip bandpass filter that uses half-wavelength line resonators. They are positioned so that adjacent resonators are parallel to each other along half of their length. This parallel arrangement gives relatively large coupling for a given spacing between resonators, and thus, this filter structure is particularly convenient for constructing filters having a wider bandwidth as compared to the other structures.

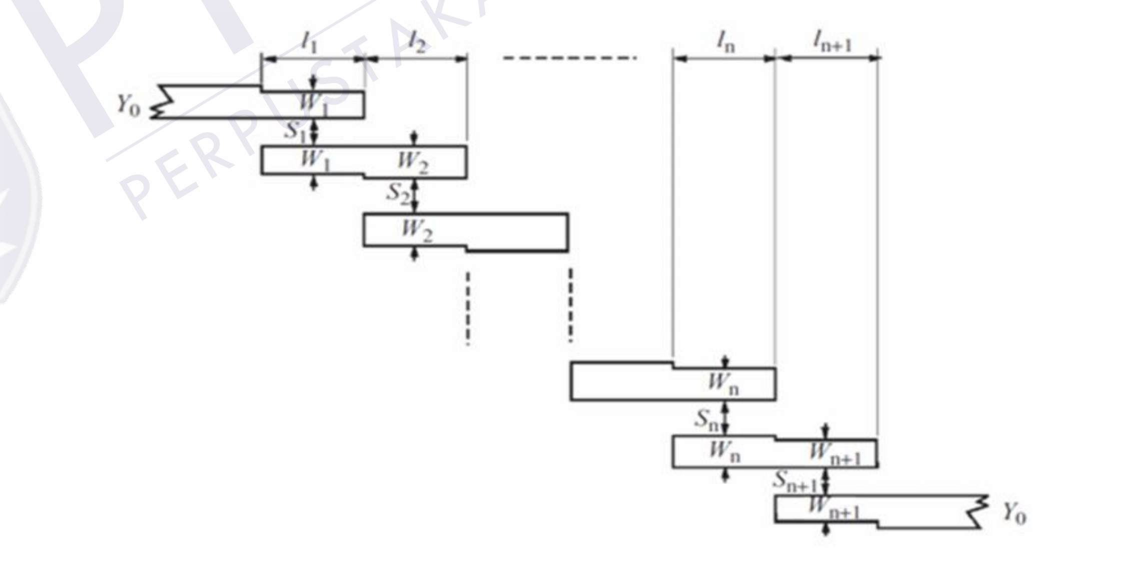

Figure 2.8 : General structure of parallel (edge)-coupled micro strip Band pass filter

Chebyshev low pass prototype with a pass-band ripple is chosen . The low pass prototype parameters are given for normalized cut-off is at - (ripple) dB where g_0, g_1, g_2, g_3, g_4 ..... g_n are the elements of low pass prototype . The filter parameters is calculated as follows:

Where a_m is ripple height

$$0.01dB = 10\log(a_m{}^2 + 1) \qquad (2.12)$$

$$a_m{}^2 = 10^{\frac{0.01}{10}} - 1 \qquad (2.13)$$

Where a is attenuation height

$$a = \sqrt{\frac{(10^{2.5} - 1)}{a_m{}^2}} \qquad (2.14)$$

Lowpass to bandpass frequency transformation

$$\omega xl = \frac{\omega_0}{\omega_2 - \omega_1}\left(\frac{\omega_x}{\omega_0} - \frac{\omega_0}{\omega_x}\right) \qquad (2.15)$$

Where n is order of filter

$$n = \frac{\mathrm{acosh}(a)}{\mathrm{acos}(\omega xl)} \qquad (2.16)$$

For first coupling section

$$\frac{J_{01}}{Y_0} = \sqrt{\frac{\pi}{2}\frac{FBW}{g_0 g_1}} \qquad (2.17)$$

For intermediate coupling section

$$\frac{J_{k+1,k}}{Y_0} = \frac{\pi FBW}{2}\frac{1}{\sqrt{g_k g_{k+1}}} \quad k = 1\ to\ n - 1 \qquad (2.18)$$

For final coupling section

$$\frac{J_{n,n+1}}{Y_0} = \sqrt{\frac{\pi}{2}\frac{FEW}{g_n g_{n+1}}} \qquad (2.19)$$

The equation 2.17 , 2.18 and 2.19 are used in parallel -coupled line filter to find even characteristic impedance (z_{0e}) and odd characteristic impedance (Z_{0o}) for J equals to 0 t o n of element by using the J-inverters, even and odd-mode impedances of coupled line microstrip line is calculated using equation 2.20 and 2.21 . In the microstrip filter , the line dimension are determined from knowledge of even and odd mode coupling line admittances which are given in term of impedance of the inverters where $Z_{0=} \frac{1}{Y}$ is the characteristic of input ,output lines of filter as shown as follows .

Even-mode characteristic impedance equation

$$(z_{0e})_{j\,j+1} = \frac{1}{Y_0}\left[1 + \frac{J_{j,j+1}}{Y_0} + \left(\frac{J_{j,j+1}}{Y_0}\right)^2\right] \qquad j = 0\, to\, n \qquad (2.20)$$

Odd-mode characteristic impedance equation

$$(z_{0o})_{j\,j+1} = \frac{1}{Y_0}\left[1 - \frac{J_{j,j+1}}{Y_0} + \left(\frac{J_{j,j+1}}{Y_0}\right)^2\right] \qquad j = 0\, to\, n \qquad (2.21)$$

2.6.2 Hairpin-Line Band Pass Filter

Hairpin-line band pass filters can be obtained by folding the resonators of parallel-coupled, half-wavelength resonator filters into a “U” shape. This type of “U” shape resonator is called hairpin resonator. Consequently, the same design equations for the parallel-coupled, half-wavelength resonator filters may be used [8]. It is widely used due to its advantages on providing flexible coupling variation and produce compact filter with simple design procedure as in [10]. The orientation of the hairpin resonator cause the electric and magnetic couplings tend to mix each other, thus resulting in maximum coupling between the adjacent resonators. A sliding factor is introduced for bending in order to make the compact circuit [11]. Folding the resonators into a "U" shape can improve the aspect ratio of the microstrip. As the frequency increased, the aspect ratio of each resonator becomes square and minimizes the size. Figure 2.9 shows the hairpin structure construct from the parallel coupled resonators.

Figure 2.9 : Haipin Resonator Structure[10]

2.6.3 Multilayer Filter

Multilayer filter technology provides another dimension in the flexible design and integration of other microwave components. There are two categories where is the first category may be composed of various coupled line resonators that are located at different layers without any ground plane inserted between the adjacent layers, as described in [12]. This type of multilayer structure is illustrated in Figure 2.10 (*a*). The Second category has aperture couplings on common ground between adjacent layers. The multilayer structure of this type is shown in Figure 2.10 (*b*). The first category is suitable for wide-band applications because stronger couplings can be easily realized and the second category would be more suitable for narrow- band applications. However, it is possible to combine these two types of multilayer structures. Wideband filter have the ratio between high cut off frequency, f_h and low cut off frequency, f_l is large than 10%. The narrow band filter have the ratio between high cut off frequency, f_h and low cut off frequency, f_l is less than 10% in which h_1 is the height of layer one and ε_1 is the dielectic of layer one similarity with other layers until layer order of n

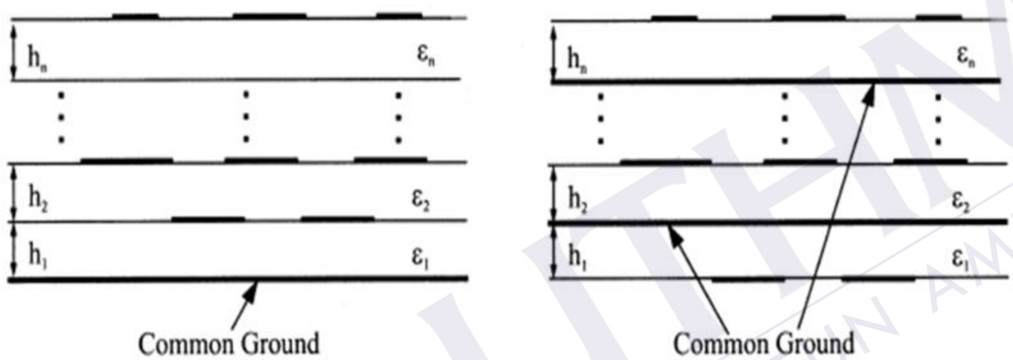

Figure 2.10 : Multilayer Structure (a) without any ground (b) with any ground plane

2.7 Filter Parameters

There are several important parameters that required to be observed in a filter design namely:

i. S-parameters

ii. Voltage Standing Wave Ratio (VSWR)

iii. Return Loss

iv. Insertion Loss

v. Bandwidth

2.7.1 S-Parameters

At low frequencies the electric behavior of circuits or components is often represented by treating them as black box with linear relationship between the input and output voltages and currents. This lead to the impedance (Z), admittance (Y) or hybrid parameter (h) matrices. However, these parameters are not suitable at microwave frequencies because the limitations in measuring the total voltage and total current at these frequencies. It is more meaningful physically to analyze microwave circuit in terms of the travelling wave components of the total voltage and current. Scattering parameter or known as S-parameter have been introduce for this purpose.

For a single transmission line with characteristic impedance Z_o, the total voltage *V*, at a distance *l* from a reference plane at *l*=0 is given by: [4]

$$V=V_i e^{j\beta l}+V_r e^{-j\beta l} \tag{2.22}$$

Where,

V_i = amplitude of the incident wave and V_r = amplitude of the reflected wave

$$a=\frac{V_i}{\sqrt{Z_o}}\ ;b=\frac{V_r}{\sqrt{Z_o}} \tag{2.23}$$

Where it is the sum of incident and reflected travelling voltage waves. S-parameters are based on normalized travelling wave voltages, ingoing wave, and outgoing wave, b that are found by dividing V_i and V_r by $\sqrt{Z_o}$.

The S-parameters at reference plane (t_1 and t_2), where *l*=0, then defining equation for the S-parameters are:

$$b_1=S_{11}a_1+S_{12}a_2 \tag{2.24}$$

$$b_2=S_{21}a_1+S_{22}a_2 \tag{2.25}$$