Abstract

The development of microwave range filter play important role in many RF or microwave applications. Filters are two port networks used to control the frequency response in an RF or microwave system by allowing transmission at frequencies within the passband of the filter, and attenuation within stopband of the filter. This research project consist of the elementary principle of microwave theory, the elementary knowledge of microwave filter design as well as fabrication and performance evaluation of Chebychev bandpass filters. The purpose of the research project is to compare the compatible microstrip filters design and the material used in the layout designs in order to get the better performance of the filter.

The insertion loss method was used to produce the parallel coupled quarter wavelength resonator filters. The compatible filter mentioned in this project able to filter out the required frequency for Digital Radio Broadcasting in the range of 1.452 GHz to 1.492 GHz. The designs were implemented using development simulation software Microwave Office 2003 (V6.01). Different prototypes of Chebychev bandpass hairpin line filters were designed. The filters were fabricated on the two different types of substrate material, which is FR4 epoxy glass and the ROGER4003C material. The entire filters design and the performances of the substrate materials to the designs are contrast. The bandwidth for FR4 hairpin filter design differs from that of the ROGER4003C design. In term of scattering parameters for S11 and S22, the ROGER4003C microstrip filter design shows low loss condition compared with FR4 filter design results. The research shows that ROGER4003C has produced better performance for the microstrip filter design.

Keywords: Chebychev, microstrip, Roger 4008C, FR4, bandpass, bandstop, hairpin.

1.0 Introduction

The rapid growth in commercial microwave technology, varies of microwave communication system had been developed such as mobile telephony, data, and television transmission. Due to the development, the frequency bands in microwave range of electromagnetic spectrum is limited and has to be shared; filters are used to select or confine the RF or microwave signal within assigned spectral limits. Hence, microstrip filters play important roles in many RF or microwave applications. Emerging applications such as wireless communications continue to challenge RF microwave filters with ever more stringent requirements higher performance, smaller size, lighter, and lower cost.

The aim of the research is to design a microstrip filter to meet the desired needs. It is a compatible filter that able to filter out certain applicable frequency range in L-Band frequency spectrum from (1 GHz - 2 GHz).

The scope of the research covers parts that determine the filter dimension, dielectric material characteristics, correspond of impedance criterion, and obtain the application frequency range.

For this microstrip filter design the applicable component was in a microstrip line form. Microwave Office 2003 (Version 6.01) application software was used to design the microstrip filter layout.

The entire fabrication was done in PCB Fabrication Laboratory and the testing was carried out using network analyzer which has inbuilt internal signal generator to supply input frequency or the filter under test.
2.0 Digital Radio Broadcasting (DRB)

Digital Radio Broadcasting (DRB) is the next generation of radio. It is a new way of broadcasting radio via a network of terrestrial transmitters. The DRB frequency range is from 1452 MHz to 1492 MHz which is in the microwave frequency range. The DRB is designed to provide CD quality sound in a mobile reception environment, the flexibility to interact with other media and the opportunity to deliver data casting. In this research the DRB frequency range had been selected for the microstrip filter design.

2.1 Filter

Filters are two port networks used to control the frequency response in an RF or microwave system by allowing transmission at frequencies within the passband of the filter, and attenuation within stopband of the filter. The ideal filter responses include low pass, high pass, bandpass and band reject (bandstop).

2.2 Chebyshev filters

The Chebyshev filter is the binomial filter exhibits a monotonic attenuation profile that is generally easy to implement. The Chebyshev response is characterized by the presence of ripple in the passband and no ripple in the stopband. The amount of ripple can be controlled, and is directly proportional to the standing wave ratio and the reflection coefficient. The cutoff frequency is specified at attenuation equal to the passband ripple. The Chebyshev response is more selective than the Butterworth response at the expense of the insertion loss and greater group delay.

2.3 Microstrip structure

The general structure of microstrip is illustrated in Figure 2.1. A conducting strip (microstrip line) with a width \(W\) and a thickness \(t\) is on the top of the dielectric substrate that has a relative dielectric constant \(\varepsilon_r\) and a thickness \(h\), and the bottom of the substrate is a ground (conducting) plane.

![Figure 2.1 Microstrip Structure](image)

2.4 Design Parameters

2.4.1 Microstrip Filter Parameter

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Attenuation Response</th>
<th>Equal Ripple Response</th>
<th>Insertion Loss</th>
<th>Impedance ((Z_0))</th>
<th>Filter Type</th>
</tr>
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<tbody>
<tr>
<td>((1.452 - 1.492)) GHz</td>
<td>30 dB</td>
<td>3.0 dB</td>
<td>3.0 dB</td>
<td>50 (\Omega)</td>
<td>Bandpass Chebyshev</td>
</tr>
</tbody>
</table>

2.4.2 Frequency Range

Lower Frequency Range, \(f_L = 1.452\) GHz

Upper Frequency Range, \(f_U = 1.492\) GHz
2.4.3 Center Frequency

\[ f_0 = \frac{f_U + f_L}{2} = \left( \frac{1492 + 1452}{2} \right) \text{MHz} = 1.472 \text{ GHz} \]

2.4.4 Bandwidth, BW

\[ BW = f_U - f_L = (1492 - 1452) \text{MHz} = 40 \text{ MHz} \]

2.4.5 Fractional Bandwidth, \( FBW (\Delta) \)

\[ \Delta = \frac{w_L - w_U}{w_0} = \frac{2\pi \left[ 1.492 \times 10^9 \right] - 2\pi \left[ 1.452 \times 10^9 \right]}{2\pi \left[ 1.472 \times 10^9 \right]} \text{Hz} = 0.027174 \]

2.4.6 Normalized Frequency; \( \Omega \)

\[ \Omega = \frac{w_0}{w_0 - w_1 \left( \frac{w_1 - w_0}{w_1 - w_0} \right)} \]

\[ \Omega = \frac{(2\pi \times 1.472 \times 10^9)}{(2\pi \times 1.492 \times 10^9) - (2\pi \times 1.452 \times 10^9)} \left( \frac{2\pi \times 1.5165 \times 10^9}{2\pi \times 1.472 \times 10^9} - \frac{2\pi \times 1.472 \times 10^9}{2\pi \times 1.5165 \times 10^9} \right) \]

\[ \Omega = 2.192355 \]

2.4.7 Ripple Factor, \( a_m \)

\[ 3.0 \text{ dB} = 10 \log_{10} \left( 1 + a_m^2 \right) \]

\[ 0.3 = \log_{10} \left( 1 + a_m^2 \right) \]

\[ 1.99526 = (1 + a_m^2) \]

\[ a_m^2 = 0.99526 \]

\[ a_m = 0.997628 \]

2.4.8 Number of Order for Circuit Element, \( n \)

For \( n \) resonator filter stopband attenuation:

\[ \text{Attenuation Response} = 10 \log_{10} \left( 1 + a_m^2 \cosh^2 \left( n \cosh^{-1} \Omega \right) \right) \]

\[ 30 \text{ dB} = 10 \log_{10} \left( 1 + 0.99526 \cosh^2 \left( n \cosh^{-1} 2.192355 \right) \right) \]

\[ 10^3 = 1 + 0.99526 \cosh^2 \left( n \cosh^{-1} 2.192355 \right) \]

\[ \cosh^2 \left( n \cosh^{-1} 2.192355 \right) = \frac{1000 - 1}{0.99526} \]

\[ \cosh \left( n \cosh^{-1} 2.192355 \right) = \sqrt{1000.7578} \]

\[ n \cosh^{-1} 2.192355 = \cosh^{-1} 31.682137 \]

\[ n = 4.14865 \]

\[ n = 1.42151 \]

\[ n = 2.91848 \]

\[ n = 3 \text{ order} \]
3.0 Design Process

The designs were fabricated using the photolithography process on different type of copper-clad board. The whole process was carried out by means of etching based on 1:1 size.

3.1 PCB material selection

There are two types of PCB material used in this research, i.e. FR4 (Fire Retardant) the most commonly used PCB material and the ROGER 4003C material which is used in many higher operating frequencies application.

Table 3.1: The PCB material specification for FR4 and the ROGER 4003C

<table>
<thead>
<tr>
<th>Material Specification Parameter</th>
<th>FR4 (Fire Retardant)</th>
<th>ROGER 4003C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Dielectric Constant, (E_r)</td>
<td>4.25</td>
<td>3.38</td>
</tr>
<tr>
<td>Substrate Thickness, (H)</td>
<td>1.6 mm</td>
<td>0.813 mm</td>
</tr>
<tr>
<td>Conductor Thickness, (T)</td>
<td>0.035 mm</td>
<td>0.017 mm</td>
</tr>
<tr>
<td>Loss Tangent of Dielectric, (T_d)</td>
<td>0.0200</td>
<td>0.0027</td>
</tr>
<tr>
<td>Substrate Material</td>
<td>Epoxy based glass</td>
<td>Ceramic Thermoset Laminates</td>
</tr>
</tbody>
</table>

Figure 3.1: The resonators are bent at the slide factor area to produce the hairpin resonator structure.

3.2 Hairpin filter design

In this design the Insertion Loss Method i.e the most common calculation method had been used. The Hairpin Filter is a variant of the edge-coupled bandpass filter. A sliding factor is introduced to allow for bending thus making the design more compact. Hairpin Filter conceptually is obtained by folding the resonators of the parallel-coupled, half-wavelength resonator filters into a "U" shape. This type of "U" shape resonator is so-called Hairpin Filter.

Figure 3.2: Graphs analysis result with the plotting points.
3.3 Microwave Filter simulator design software (Microwave Office 2003, Version 6.01)

Microwave Office (MWO) enables to design circuits composed of schematics and electromagnetic (EM) structures from an extensive electrical model database, and then generate layout representations of these designs. The output of the design showed in a wide variety of graphical forms based on the analysis needs (see Fig. 3.2). The advanced tunable tool in this software enables to tune or optimize the designs and the changes are automatically and immediately reflected in the layout. By this way designers can see the effects of the test signals before investing in hardware prototypes.

The MWO simulation design procedure consists of several basic operations and steps to performing the following tasks in the AWR (Applied Wave Research) Design Environment:

- Creating projects to organize and save the designs.
- Creating system diagrams, circuit schematics, and EM structures.
- Placing circuit elements into schematics.
- Placing system blocks into system diagrams.
- Creating and displaying output graphs.
- Running simulations for schematics and system diagrams.
- Tuning simulations.
- Creating layouts.

3.4 Microwave filter fabrication

The circuit pattern is realized by the photolithographic process. A mask of the circuit to be realized is drawn at a suitable scale, cut, and then reduced and placed on top of a photoresistive layer, which was previously deposited on top of the microstrip. The structure is then exposed to ultraviolet radiation, which reaches the photosensitive layers through the mask openings. The exposed parts are removed by the photographic development, and the metal cover is etched away from the exposed area. It is also possible to deposit metal by evaporation or sputtering upon a bare dielectric substrate.

In this research project the testing process was carried out using the R3765/67G series network analyzer. A network analyzer makes measurements of S-parameter S11 and S21, SWR, Smith Chart for impedance matching and etc.

4.0 Result and Analysis

This filters were tested using the Microwave Office 2003 (Version 6.01) simulation software, and testing equipment “R3765G/67G-Series” vector network analyzer. The outcome of each microwave filters are determined; analysis is referred to the structure of the designs and also the scattering parameters which are obtained from the simulation software and network analyzer.

4.1 The characteristics of hairpin line microstrip bandpass filters design.

Figure 4.1 showed the schematic design of hairpin line microstrip bandpass filter using the FR4 and ROGER 4003C material designs. The substrate material specification and the elements parameter is based on the calculation.

Figure 4.1: Schematic design for hairpin line bandpass filter (HPF).
The hairpin filter configuration is derived from the coupled line filter. To improve the aspect ratio, the resonators are folded into a “U” shape. Each resonator of the hairpin filter is 180 degrees so that the length from the center to either end of the resonator is 90 degrees. This design reduces the coupled line lengths and, in effect reduces the coupling between resonators.

The microstrip filter simulation design has been done with the real time tuning, which all the variables of the dimension (width, spacing and length) had been changed in order to get the yield of the project specification. After the real time tuning the layout design is generated out as shown in Figure 4.2 and Figure 4.3.

![Figure 4.2: Hairpin line layout design using FR4 material microstrip filter layout in 2D and 3D mode](image)

![Figure 4.3: Hairpin line layout design Using ROGER4003C material microstrip filter layout in 2D and 3D mode](image)

### 4.2 The comparison for the same design patterns between two different materials.

Table 4.1 is the hairpin line microstrip filter layout dimensions using FR4 material and ROGER4003C material for the design after the real time tuning results with the supported variable or equation syntax value, which it can represent the dimensions for anywhere of the transmission line elements that we placed it.

<table>
<thead>
<tr>
<th>Element</th>
<th>Type of design</th>
<th>FR4 HPF Less or Greater ROGER4003C HPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLn (W0)</td>
<td>3.0660</td>
<td>&gt; 1.4000</td>
</tr>
<tr>
<td>TLn (W1)</td>
<td>3.0660</td>
<td>&gt; 1.3000</td>
</tr>
<tr>
<td>TLn (S0)</td>
<td>1.3350</td>
<td>&gt; 0.7790</td>
</tr>
<tr>
<td>TLn (S1)</td>
<td>3.7270</td>
<td>&gt; 2.1770</td>
</tr>
<tr>
<td>TLn (S2)</td>
<td>3.8970</td>
<td>&gt; 2.3270</td>
</tr>
<tr>
<td>TLn (S3)</td>
<td>1.7450</td>
<td>&gt; 1.0400</td>
</tr>
<tr>
<td>TLn (L0)</td>
<td>25.1000</td>
<td>&lt; 27.5000</td>
</tr>
<tr>
<td>TLn (L1)</td>
<td>20.5900</td>
<td>&lt; 24.5000</td>
</tr>
<tr>
<td>TLn (L2)</td>
<td>1.0590</td>
<td>&lt; 3.7280</td>
</tr>
<tr>
<td>TLn (L3)</td>
<td>3.2440</td>
<td>&lt; 5.2240</td>
</tr>
<tr>
<td>TLn (L4)</td>
<td>19.0000</td>
<td>&gt; 8.0000</td>
</tr>
</tbody>
</table>

**Note:** HPF: Hairpin Filter, TLn is the transmission line elements from the schematic design. The (Wn, Sn and Ln) is the variable or equation syntax for the transmission line width, spacing and length respectively.

Based on layout dimensions comparison from the simulation software for the hairpin line microstrip bandpass filter design, which use difference type of substrate material (FR4 and ROGER4003C) had shown that the filter design with FR4 material will produce the width and the gap of the transmission lines greater than the filter transmission lines design by using the ROGER4003C material.

Eventually, the dimensions of the microstrip filter layout design is due to the material specifications in term of the dielectric constant values that affect the length size of the design, which mean that the greater the dielectric constant values will decrease the size of length. For the substrate thickness material specification it is equal proportional to the...
layout design width and gap sizes. The decrease of the substrate thickness will reduce the transmission lines width and gap. These circumstances had been proved by the calculation work in previous section.

4.3 Test results analysis

Figure 4.4 Hairpin Filter Design: Chebyshev bandpass response for microstrip filter design using FR4 material

Figure 4.5 Hairpin Filter Design: Chebyshev bandpass response for microstrip filter design using ROGER4003C material

Figure 4.6 Hairpin Filter Design: Smith Chart result for ROGER4003C material microstrip filter design
Figures 4.4 and 4.5 show the frequency response of the filter for FR4 and ROGER 4003C respectively. While Figures 4.6 and 4.7 show the Smith Chart pattern for both FR4 and ROGER 4003C. The presence of two ripple peaks in the response conforms the criteria fixed in the Chebyshev design.

For the FR4 hairpin line design in Figure 4.8 the bandpass response is out of the desired passband frequency range because the center frequency is located in the higher frequency band, although the 3dB bandwidth is 36.1434 MHz with the Q factor of 39.8170. In addition, by observing the response curve, it exhibited an asymmetrical frequency response and the stopband is attenuated less than 30dB.

For the Figure 4.9 ROGER4003C HPF design the bandpass response is quite adequately to the desired frequencies. From the test shown in Figure 4.9, the hairpin line filter with the folded resonator that uses strong coupling, folded resonators employing the coupling scheme described above achieves a relatively low insertion loss and good return loss characteristics.
The following Figure 4.10 shows the actual hairpin line filter design on ROGER 4003C and FR4.

![Image](a) & (b)

Figure 4.10: The dimension for (a) ROGER4003C, (b) FR4 hairpin line filter (6 mm)

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>Measurement</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(S21) Insetion Loss (dB)</td>
<td>(S11) Return Loss (dB)</td>
</tr>
<tr>
<td>FR4 HPFS</td>
<td>-19.8000</td>
<td>-7.1770</td>
</tr>
<tr>
<td>ROGER4003C HPF</td>
<td>-4.0010</td>
<td>-19.9080</td>
</tr>
</tbody>
</table>

Table 4.2: The comparison results of insertion loss and return loss for the designs

Based from the result as shown in Table 4.2 it shows that the microstrip filter which used the FR4 material has introduced much higher losses especially in the insertion loss (S21) above -10dB and the return loss (S11) is considerably small. While the design used the ROGER4003C material the result is much better.

![Graph](SWR graph)

Figure 4.11 Hairpin Filter Design - SWR test results from the S11 parameter for FR4 design material

![Graph](SWR graph)

Figure 4.12 Hairpin Filter Design - SWR test results from the S11 parameter for ROGER4003C design material
Table 4.3: SWR measured values for the entire designs

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>SWR</th>
<th>Simulation</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4 HPFS</td>
<td>1.3320</td>
<td>1.1040</td>
<td>20.6520</td>
</tr>
<tr>
<td>ROGER4003C HPF</td>
<td>1.2290</td>
<td>1.0890</td>
<td>12.8560</td>
</tr>
</tbody>
</table>

The data for Table 4.3 is depicted from Figure 4.11 and Figure 4.12. The SWR is the ratio of the maximum to minimum values of the ‘standing wave’ pattern that is created when signals are reflected on a transmission line and it also can be used to determine the mismatch of a line.

The microstrip filter design using FR4 material has the high SWR result, therefore the return loss is small. Hence, it affected the circuit design to become mismatch, this will increase the reflection and the filter will have the problem to filter the desired signal into the passband. While for the designs using ROGER4003C material the results is vice versa.

Table 4.4: The impedance matching results for the entire designs

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>Impedance Matching, S11 (Ohm)</th>
<th>Specification Z₀ (Ohm)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4 HPFS</td>
<td>59.2040</td>
<td>50</td>
<td>18.4080</td>
</tr>
<tr>
<td>ROGER4003C HPF</td>
<td>42.0780</td>
<td>50</td>
<td>15.8440</td>
</tr>
</tbody>
</table>

The Smith chart measurement results indicated that the designs, using FR4 material depicted in Figure 4.7 have small return loss and high insertion loss. Table 4.4 shows the impedance matching for FR4 is 59.204 Ohm. Therefore the load is not matched to the $Z₀$ of the line and the structures will consequence the reflection on the circuit.

The Smith Chart of Figure 14.13 shows the result of the test for the design with ROGER4003C. An almost perfect circle on the chart was formed that used to identify the reflection coefficient and the function of frequency. From the result also shown that the design with ROGER4003C material had given better impedance matching results. This is because the material has low loss tangent value and it is good to be used in any microwave application.

5. CONCLUSIONS

To obtain microwave filter with better value, substrate other than epoxy FR4 and ROGER4003 should be used. Substrate RT/duriod will give better outcome 6010LM with the high dielectric constant 10.2, tolerance ±0.25 and loss factor of 0.0023 as compared with FR4 with low dielectric constant 4.25 and high loss factor of 0.02.

The photolithography fabrication results out of our designated dimensions. Care is required in the fabrication to ensure proper circuit operation. Meanwhile, micromachining technology should be introduced to produce microstrip filter devices with higher performance.

The accuracy of the entire microstrip filters compared to the actual parameter was acceptable and the microstrip filters had successfully produced the bandpass response. It was found that the design using glass reinforced hydrocarbon / ceramic thermoset laminates material (ROGER4003C), has decreased the final size of the filter compared to that of the Epoxy glass (FR4). In term of the scattering parameters S11 for return loss and S21 for insertion loss measurements, the filter design using ROGER4003C material obviously given low insertion loss and greater in return loss, which similar to the simulation design.
Based on the results of the tests to the two different types of materials for microstrip filter design, the ROGER 4003C has better performance than the FR4. However, in term of bandwidth, it was obvious that the design using ROGER 4003C had a bigger bandwidth with lower Q factor value than the design with FR4. The FR4 material has a bigger Q but lower bandwidth. The Q factor is considered as an important factor when judging the performance of the microwave filter. For a good microwave filter, a large Q factor and a small bandwidth are desirable where the larger the Q factor, the better the selectivity of a microwave filter.

REFERENCES


Comparison of Digital Radio Broadcasting Frequency Coupled Line Filter and Hairpin Filter Designs Using FR4

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1. INTRODUCTION

The rapid growth in commercial microwave technology, varies of microwave communication system had been developed such as mobile telephony, data, and television transmission. Due to the development, the frequency bands in microwave range of electromagnetic spectrum is limited and has to be shared; filters are used to select or confine the RF or microwave signal within assigned spectral limits. Hence, microstrip filters play important roles in many RF or microwave applications. Emerging applications such as wireless communications continue to challenge RF microwave filters with ever more stringent requirements higher performance, smaller size, lighter, and lower cost.

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Digital Radio Broadcasting (DRB) is the next generation of radio. It is a new way of broadcasting radio via a network of terrestrial transmitters. The DRB frequency range is from 1452 MHz to 1492 MHz which is in the microwave frequency range [2]. The DRB is designed to provide CD quality sound in a mobile reception environment, the flexibility to interact with other media and the opportunity to deliver data casting. In this research the DRB frequency range had been selected for the microstrip filter design.
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2.3 Microstrip structure

The general structure of microstrip is illustrated in Figure 2.1. A conducting strip (microstrip line) with a width \( W \) and a thickness \( t \) is on the top of the dielectric substrate that has a relative dielectric constant \( \varepsilon_r \) and a thickness \( h \), and the bottom of the substrate is a ground (conducting) plane [4].

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2.4.2 Frequency Range

Lower Frequency Range, \( f_L = 1.452 \) GHz
Upper Frequency Range, \( f_U = 1.492 \) GHz

2.4.3 Center Frequency

\[
f_o = \frac{f_U + f_L}{2} = \left( \frac{1492 + 1452}{2} \right) \text{MHz} = 1.472 \text{GHz}
\]

2.4.4 Bandwidth, \( BW \)

\[
BW = f_U - f_L = (1492 - 1452) \text{MHz} = 40 \text{MHz}
\]

2.4.5 Fractional Bandwidth, \( FBW (\Delta) \)

\[
\Delta = \frac{w_U - w_L}{w_O} = \frac{2\pi(1.492 \times 10^9) - 2\pi(1.452 \times 10^9)}{2\pi(1.472 \times 10^9)} \text{Hz} = 0.02714
\]
2.4.6 Normalized Frequency; $\Omega$

$$\Omega = \frac{w_0}{w_2} \left( \frac{W_w}{w_0} \right)$$

$$\Omega = \frac{(2\pi \times 1.472 \times 10^9)}{(2\pi \times 1.492 \times 10^9) - (2\pi \times 1.452 \times 10^9)} \left( \frac{2\pi \times 1.5165 \times 10^9 \times 2\pi \times 1.472 \times 10^9}{2\pi \times 1.5165 \times 10^9} \right)$$

$$\Omega = 2.192355$$

2.4.7 Ripple Factor, $a_m$

$$IL = 10 \log_{10} \left( 1 + a_m^2 \right)$$

$$3.0 \ dB = 10 \log_{10} \left( 1 + a_m^2 \right)$$

$$0.3 = \log_{10} \left( 1 + a_m^2 \right)$$

$$1.99526 = \left( 1 + a_m^2 \right)$$

$$a_m^2 = 0.99526$$

$$a_m = 0.997628$$

2.4.8 Number of Order for Circuit Element, $n = 3$

For $n$ resonator filter stopband attenuation;

Attenuation Response = $10 \log_{10} \left[ 1 + a_m^2 \cosh^2 \left( n \cosh^{-1} \Omega \right) \right]$

30 dB = $10 \log_{10} \left[ 1 + 0.99526 \cosh^2 \left( n \cosh^{-1} 2.192355 \right) \right]$

$10^3 = 1 + 0.99526 \cosh^2 \left( n \cosh^{-1} 2.192355 \right)$

$\cosh^2 \left( n \cosh^{-1} 2.192355 \right) = 1 + 0.99526$

$cosh \left( n \cosh^{-1} 2.192355 \right) = \sqrt{1003.7578}$

$n \cosh^{-1} 2.192355 = \cosh^{-1} 31.682137$

$n = 4.14865$

$n = 1.42151$

$n = 2.91848$

$n \approx 3$ order

3. DESIGN PROCESS

Table 3.1: The PCB material specification for FR4

<table>
<thead>
<tr>
<th>Material Specification Parameter</th>
<th>FR4 (Fire Retardant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Dielectric Constant, (Er)</td>
<td>4.25</td>
</tr>
<tr>
<td>Substrate Thickness, (H)</td>
<td>1.6 mm</td>
</tr>
<tr>
<td>Conductor Thickness, (T)</td>
<td>0.035 mm</td>
</tr>
<tr>
<td>Loss Tangent of Dielectric, (Tand)</td>
<td>0.0200</td>
</tr>
<tr>
<td>Substrate Material</td>
<td>Epoxy based glass</td>
</tr>
</tbody>
</table>

3.1 PCB material selection

FR4 (Fire Retardant) PCB material was used in this research work. It is the most commonly used PCB material in many microwave filter fabrications. The specification of the material is shown in Table 3.1.
3.2 Coupled Line Filter Design

Figure 3.2 shows the schematic designs for coupled line filter design using the FR4 material. The substrate material specification and the elements parameter is based on the calculation work in parameter design section 2.4.

The hairpin filter configuration is derived from the coupled line filter. To improve the aspect ratio, the resonators are folded into a “U” shape. Each resonator of the hairpin filter is 180 degrees so that the length from the center to either end of the resonator is 90 degrees. From 90 degrees, 9 degrees are “slide” out of the coupled section into the uncoupled segment of the resonator (fold of the resonator). This reduces the coupled line lengths and, in effect, reduces the coupling between resonators. One guide in choosing the slide factor of the filter is the correlation of the resonator self-spacing and the mutual spacing of the resonators. Studies of few examples suggest that resonator self-spacing 2 to 2.5 times larger than the mutual spacing are sufficient. As the slide factor is reduced the arms of the hairpin resonators become more closely spaced. This introduces resonator self-coupling that narrows the bandwidth and increases the insertion loss of the hairpin filter.
Figure 3.3: Schematic designs for hairpin line bandpass filter (HPF).

The two filter designs in simulation have been carried out with real time tuning which all the variables of the dimension (width, spacing and length) been adjusted and changed in order to get the yield of the project specification. After the real time tuning the layout design is generated as shown in Figure 4.1.

3.3 Microwave filter fabrication

The circuit patterns of Figure 4.1 are realized by the photolithographic process. A mask of the circuit to be realized is drawn at a suitable scale, cut, and then reduced and placed on top of a photoresistive layer, which was previously deposited on top of the microstrip. The structure is then exposed to ultraviolet radiation, which reaches the photosensitive layers through the mask openings. The exposed parts are removed by the photographic development, and the metal cover is etched away from the exposed area. It is also possible to deposit metal by evaporation or sputtering upon a bare dielectric substrate. In this research project the testing process was carried out using the R3765/67G series network analyzer. A network analyzer makes measurements of S-parameter S11 and S21, SWR, Smith Chart for impedance matching and etc.

4. RESULT AND ANALYSIS

This section discusses about all the results and analysis based on the result obtained using Microwave Office 2003 (Version 6.01) simulation software, and testing equipment “R3765G/67G-Series” vector network analyzer. The outcome of each microwave filters are determined; analysis is referred to the structure of the designs and also the scattering parameters which are obtained from the simulation software and network analyzer.

4.1 The layout of microstrip band pass filter designs

Figure 4.1: FR4 material microstrip filter layout in 2D and 3D mode
(a) Coupled line layout design. (b) Hairpin line layout design.
Figure 4.1 shows the schematic design of coupled-line and hairpin line microstrip bandpass filter using the FR4 material. The substrate material specification and the elements parameter is based on the calculation. The hairpin filter configuration is derived from the coupled line filter. To improve the aspect ratio, the resonators are folded into a "U" shape. Each resonator of the hairpin filter is 180 degrees so that the length from the center to either end of the resonator is 90 degrees. This design reduces the coupled line lengths and, in effect reduces the coupling between resonators.

The microstrip filter simulation design has been done with the real time tuning, which all the variables of the dimension (width, spacing and length) had been changed in order to get the yield of the project specification.

4.2 The comparison for the different design patterns on the same material

Table 4.1 is the hairpin line microstrip filter layout dimensions using FR4 material for the design after the real time tuning results with the supported variable or equation syntax value, which can represent the dimensions at any point of the transmission line elements that we placed it. Based on layout dimensions comparison from the simulation software for the hairpin line microstrip bandpass filter design, which use the same type of substrate material (FR4), had shown that the width and gap of the transmission lines CLF design were greater than that of the HPF design.

The dimensions of the microstrip filter layout design depend on the material specifications in term of the dielectric constant values that affect the length size of the design, which mean that the greater the dielectric constant values, the smaller will be the length. For the substrate thickness material specification it is proportional to the layout design width and gap sizes. The decrease in the substrate thickness will reduce the transmission lines width and gap. These circumstances had been proved by the calculation work in previous section.

Table 4.1: The hairpin line layout design dimensions. Table 4.2: The coupled-line layout design dimensions.

<table>
<thead>
<tr>
<th>Element</th>
<th>FR4 HPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLn (W0)</td>
<td>3.0660</td>
</tr>
<tr>
<td>TLn (W1)</td>
<td>3.0660</td>
</tr>
<tr>
<td>TLn (S0)</td>
<td>1.3350</td>
</tr>
<tr>
<td>TLn (S1)</td>
<td>3.7270</td>
</tr>
<tr>
<td>TLn (S2)</td>
<td>3.8970</td>
</tr>
<tr>
<td>TLn (S3)</td>
<td>1.7450</td>
</tr>
<tr>
<td>TLn (L0)</td>
<td>25.1000</td>
</tr>
<tr>
<td>TLn (L1)</td>
<td>20.5900</td>
</tr>
<tr>
<td>TLn (L2)</td>
<td>1.0590</td>
</tr>
<tr>
<td>TLn (L3)</td>
<td>3.2440</td>
</tr>
<tr>
<td>TLn (L4)</td>
<td>19.0000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>FR4 CLF (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL1 (W)</td>
<td>4.0360</td>
</tr>
<tr>
<td>TL1 (S)</td>
<td>27.0000</td>
</tr>
<tr>
<td>TL2 (W)</td>
<td>3.6250</td>
</tr>
<tr>
<td>TL2 (S)</td>
<td>1.6410</td>
</tr>
<tr>
<td>TL2 (L)</td>
<td>27.4000</td>
</tr>
<tr>
<td>TL3 (W)</td>
<td>3.3510</td>
</tr>
<tr>
<td>TL3 (S)</td>
<td>4.9470</td>
</tr>
<tr>
<td>TL3 (L)</td>
<td>27.5000</td>
</tr>
<tr>
<td>TL4 (W)</td>
<td>3.3510</td>
</tr>
<tr>
<td>TL4 (S)</td>
<td>4.9470</td>
</tr>
<tr>
<td>TL4 (L)</td>
<td>27.5000</td>
</tr>
<tr>
<td>TL5 (W)</td>
<td>3.6250</td>
</tr>
<tr>
<td>TL5 (S)</td>
<td>1.8210</td>
</tr>
<tr>
<td>TL5 (L)</td>
<td>27.4000</td>
</tr>
<tr>
<td>TL6 (W)</td>
<td>4.0360</td>
</tr>
<tr>
<td>TL6 (L)</td>
<td>27.0000</td>
</tr>
</tbody>
</table>

Note: TLn is the transmission line elements from the schematic design. The (Wn, Sn and Ln) is the variable or equation syntax for the transmission line width, spacing and length respectively.

Note: TLn is the transmission line elements from the schematic design. W is the width for the transmission line. S is the spacing in between two coupling transmission line. L is the length for the transmission line.
4.3 The frequency response of the designs

![Frequency response graphs for FR4 CLF and FR4 HPF designs.](image)

Figure 4.2 Chebyshev bandpass response for microstrip filter design using FR4 material
(a) CLF line design response, (b) HPF design response.

According to the simulation results from Figure 4.2 (a) and (b), it is the Chebyshev bandpass filter response which designed in fractional bandwidth of 2.7174 percent and all the results shown the rejection levels at the response dips or roll-off are better than -50dB. The insertion loss (S21) signal for the entire designs is less than -2dB, while the return loss (S11) signal response is more than -25dB. It can be observed that all the simulation bandpass filter responses have a good agreement in both the passband and stopband.

4.4 3dB ripple response of the designs

By referring to Figure 4.2 (a) and (b) there are 3 ripples occurred on top of the insertion loss signal (S11). These Chebyshev passband ripples response is equal to the order and number of reactive elements in the Chebyshev prototype which had specified in Section 2.4.

Table 4.3: The 3dB response result for the entire microstrip filters design.

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>Lowest Ripple Point (dB)</th>
<th>Highest Ripple Point (dB)</th>
<th>3dB Ripple Response (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4 CLF</td>
<td>4.0535</td>
<td>1.3588</td>
<td>2.6947</td>
</tr>
<tr>
<td>FR4 HPF</td>
<td>4.1901</td>
<td>1.6816</td>
<td>2.5085</td>
</tr>
</tbody>
</table>

Table 4.3 is the result to define 3 dB ripples response from the entire Chebyshev bandpass filters design. From the table, HPF has the highest ripples point, with better selectivity.

4.5 3dB cut-off frequency response

Two normal definitions for the cutoff of Chebyshev filters are often used. Some contributors have defined the cutoff attenuation as 3 dB, and others define the cutoff attenuation as the passband ripple value, with the latter perhaps somewhat more generally accepted.

Table 4.4: The entire designs result of 3dB cut-off frequency response.

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>Insertion Loss (S21) Peak Point (dB)</th>
<th>Lower Cut-off Frequency Point (dB)</th>
<th>3dB Cut-off Frequency Response (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4 CLF</td>
<td>1.3588</td>
<td>4.8862</td>
<td>3.5274</td>
</tr>
<tr>
<td>FR4 HPF</td>
<td>1.6816</td>
<td>5.5804</td>
<td>3.8988</td>
</tr>
</tbody>
</table>
Table 4.4 shows the 3dB cut-off frequency response for all designs is beyond 3dB value. However, Chebyshev bandpass filter allows the user to specify any attenuation equal to or greater than the ripple attenuation as the cutoff. Any of the cutoff attenuation greater than the ripple may be specified for the Chebyshev response.

### 4.6 3dB bandwidth response

The 3dB bandwidth is typically reference to the 3 dB bandwidth points of a bandpass filters passband. Table 4.5 notices that all the microstrip filters design has the 3dB bandwidth quite close to the design specification which is 40MHz.

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>Lower Frequency (GHz)</th>
<th>Upper Frequency (GHz)</th>
<th>3dB Bandwidth (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4 CLF</td>
<td>1.4521</td>
<td>1.4917</td>
<td>39.6000</td>
</tr>
<tr>
<td>FR4 HPF</td>
<td>1.4526</td>
<td>1.4927</td>
<td>40.1000</td>
</tr>
</tbody>
</table>

### 4.7 The comparison of the Smith chart results for the designs

The Smith chart is a graph that allows all passive impedances or admittances to be plotted in a reflection coefficient chart of unit radius. For this measurement the resonator only needs one port which means that S11 parameter is taking into consideration. The beauty of this measurement is a perfect circle that the measured reflection coefficient, plotted on a Smith chart, describes as a function of frequency. If there is no any perfect circle, then it is something wrong with the reference position. If the center frequency (f0) is located at the center of the Smith chart, then the magnitude |r| is plotted as a radius (|r| ≤ 1) from the center of the chart, and the angle θ(-180° ≤ θ ≤ 180°) is measured from the right-hand side of the horizontal diameter. Any passively realizable (|r| ≤ 1) reflection coefficient can then be plotted as a unique point on the Smith chart. On the other hand the Smith chart used for the analysis of circuit impedances, design of matching network. Figure 4.3 and Figure 4.4 showed the simulation Smith chart results for the entire designs.

![Smith Chart](image)

**Figure 4.3 Smith Chart (a) FR4 CLF (b) FR4 HPF**

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>Magnitude (Ohm)</th>
<th>Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4 CLF</td>
<td>50.4190</td>
<td>4.2345°</td>
</tr>
<tr>
<td>FR4 HPF</td>
<td>50.0880</td>
<td>-0.1695°</td>
</tr>
</tbody>
</table>

Table 4.6 shows the result of impedance matching obtained from the Smith Chart. It was found that FR4 HPF has better impedance matching compared with the FR4 CLF.

4.8 The test result

Figure 4.4 is the LOG MAG (Magnitude in dB) graph or known as a rectangular graph test results for the 3dB bandwidth Chebyshev bandpass response. Generally, the testing results shown all the designs had successfully come out with the bandpass signal response.

Table 4.7: LOG MAG results for 3dB bandwidth response of microstrip filters design using FR4 material.

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>PO (GHz)</th>
<th>differ</th>
<th>differ %</th>
<th>BW (MHz)</th>
<th>differ</th>
<th>BW (MHz)</th>
<th>differ %</th>
<th>Q factor</th>
<th>differ</th>
<th>differ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specification</td>
<td>1.4720</td>
<td>-0.0120</td>
<td>0.8152</td>
<td>43.6716</td>
<td>3.6716</td>
<td>9.1950</td>
<td>33.4310</td>
<td>3.3650</td>
<td>9.1549</td>
<td></td>
</tr>
<tr>
<td>FR4 CLF</td>
<td>1.4600</td>
<td>0.1318</td>
<td>8.9531</td>
<td>40.9496</td>
<td>0.9496</td>
<td>2.3740</td>
<td>39.1650</td>
<td>2.3650</td>
<td>6.4266</td>
<td></td>
</tr>
<tr>
<td>FR4 HPF</td>
<td>1.6038</td>
<td>0.3118</td>
<td>8.9531</td>
<td>40.9496</td>
<td>0.9496</td>
<td>2.3740</td>
<td>39.1650</td>
<td>2.3650</td>
<td>6.4266</td>
<td></td>
</tr>
</tbody>
</table>

(a) (b)

Figure 4.4: 3dB bandwidth test result for Chebyshev bandpass response design using FR4 material (a) Coupled line design CLF (b) Hairpin line design HPF

Table 4.8: The insertion loss and return loss for the FR4 CLF and HPF designs in between the measured and simulation results

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>Measurement</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(S21) Insertion Loss (dB)</td>
<td>(S11) Return Loss (dB)</td>
</tr>
<tr>
<td>FR4 HPF</td>
<td>-20.6920</td>
<td>-8.5570</td>
</tr>
</tbody>
</table>

In Figure 4.4 (a) the FR4 coupled line design showing the 3dB bandwidth with a symmetrical response. The center frequency output result is quite close to the desired frequency, it is just 0.8152 % different with the specification frequency. The bandpass response is shifted 12 MHz to the lower range. Seem the bandwidth is greater than the...
specification bandwidth of 3.6716 MHz, so the Q factor value is less than the specification as well as simulated Q factor values. Subsequently, the bandpass response showed that the 30dB attenuation response for the rejection level has a good agreement with the desired specification. For the FR4 hairpin line design in Figure 4.4 (b) the bandpass response is out of the desired passband frequency range because the center frequency is located in the higher frequency range, although the 3dB bandwidth is 40.9496 MHz with the Q factor of 39.165 much better than the FR4 CLF design. In addition, by observing the response curve, it exhibited an asymmetrical frequency response and the stopband is attenuated less than 30dB. Beside that, there are no ripples reveal at the passband response because of high insertion loss (S21) and small return loss (S11) response.

Generally, the practical insertion loss measurement result obtained for overall fabricated microstrip filters design are higher than the insertion loss obtained from the simulation designs. This is due to the imperfection of the filter structure or microstrip line and the roughness of the microstrip surface cause of losses. The I/O port of the SMA connector connection during handling the soldering process also contributes to the insertion loss and it is also partly because of the testing apparatus such as coaxial cables and the connectors of the network analyzer. Thus it introduces high losses to the physical designs.

The difference of bandwidth is caused by the inaccuracy of fabrication process causing the measurement of the microstrip lines to differ from the actual design. The narrowing of the spacing causes the bandwidth to increase and vice versa. The major factor that contributing to the varying of the bandwidth is the imprecision of the equipment used for fabrication processes which only has the sensitivity up to ±0.5mm.

Figure 4.5: Smith chart results for Chebyshev bandpass response design using FR4 material (a) Coupled line design (b) Hairpin line design

Table 4.9: The impedance matching results for the entire designs.

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>Impedance Matching, S11 (Ohm)</th>
<th>Specification Z0 (Ohm)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4 CLF</td>
<td>87.218</td>
<td>50</td>
<td>74.436</td>
</tr>
<tr>
<td>FR4 HPF</td>
<td>107.567</td>
<td>50</td>
<td>115.134</td>
</tr>
</tbody>
</table>

The Smith chart measurement results indicated that the designs, which using the FR4 material depicted in Figure 4.5 have small return loss and high insertion loss. The impedance matching is 87.218 Ohm for the CLF design with the difference of 74.436 percent to the required value. While the HPF designs the impedance matching is much bigger 107.567. Therefore the load is not matched to the Z0 of the line and the structures will consequence the reflection on the circuit. So the insertion loss is high and the bandwidth is widened. Analysis shows that the mismatch is mainly due to the deviation of the value of the coupling capacitors between the resonators created in fabrication. Loss is due both to the
The microstrip filter design of CLF using FR4 material considerably has higher SWR compared to HPF, therefore the overall return loss is small. Hence, it affected the circuit design to become mismatch, this will increase the reflection and the filter will have the problem to filter the desired signal into the passband. The Smith chart measurement results indicated that the designs, using FR4 material have small return loss and high insertion loss as shown in Table 4.8. Therefore the load is not matched to the $Z_0$ of the line and consequently caused higher insertion loss to the circuit.

5. CONCLUSIONS

To obtain microwave filter with better value, substrate other than epoxy FR4 should be used. Substrate RT/duroid will give better outcome 6010LM with the high dielectric constant 10.2, tolerance ±0.25 and loss factor of 0.0023 as compared with FR4 with low dielectric constant 4.25 and high loss factor of 0.02.

The photolithography fabrication results out of the designated dimensions. Care is required in the fabrication to ensure proper circuit operation. Meanwhile, micromachining technology should be introduced to produce microstrip filter devices with higher performance.

The accuracy of the entire microstrip filters compared to the actual parameter was acceptable and the microstrip filters had successfully produced the bandpass response. In term of the scattering parameters S11 for return loss and S21 for insertion loss measurements, the CLF filter design obviously given lower insertion loss than HPF. Based on the results of the tests of the two different types of designs, on overall the HPF has better performance than the CLF. This is based on the coefficient of reflection and return loss. However in some expect, CLF has got some advantage, especially on the impedance matching S11. The FR4 material has a bigger Q but lower bandwidth. The Q factor is considered as an important factor when judging the performance of the microwave filter. For a good microwave filter, a large Q factor and a small bandwidth are desirable where the larger the Q factor, the better the selectivity of a microwave filter.

REFERENCES


finite conductivity of the metal and to the dissipation of the dielectric material used to construct the line. The frequency
dependence of these effects and the change in electromagnetic field distributions with wavelength together give rise to
dispersion.

In order to produce a good design the consideration of the impedance matching just as with the source, if $Z_0$, transmission
line drives a load of $Z_0$ there is no reflection, hence no standing wave pattern, maximum power is transferred, and
measurements are greatly simplified. Thus to minimize reflections and maximize measurement accuracy, microwave
instruments have test port impedances equal to the characteristic impedance of microwave coaxial cable and connectors
($Z_0 = 50$ Ohm).

Table 4.10: SWR measured values for the entire designs.

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>SWR</th>
<th>Reflection Coefficient</th>
<th>Return Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4 CLF</td>
<td>2.395</td>
<td>0.4109</td>
<td>7.7253</td>
</tr>
<tr>
<td>FR4 HPF</td>
<td>2.185</td>
<td>0.3721</td>
<td>8.5878</td>
</tr>
</tbody>
</table>

The Table 4.10 shows that the SWR and reflection coefficient of the FR4 CLF and FR4 HPF. It is found that FR4 CLF has
higher SWR and therefore lower return loss compared with the FR4 HPF. Hence, it affected the circuit design become
mismatch, this will increase the reflection and the filter will have the problem to filter the desired signal into the passband.
The SWR due to the standing wave within the transmission line is often used to quantify how well a part is impedance
matched. Always expressed as a ratio to unity, a SWR of 1.0:1 indicates perfection (there is no standing wave). A SWR of
2:1 means the maxima are twice the voltage of the minima. A high SWR such as 10:1 usually indicates the system have
problem, such as a near open or near short circuit. The mismatched occurrence at the designs is mainly due to the
deviation of the value of the coupling capacitors between the resonators created in fabrication.

(a) (b)

Figure 4.6: SWR test results from the S11 parameter for FR4 design material (a) FR4 CLF design (b) FR4 HPF design.

4.9 Improving the grounding condition of the design

For the coupled-line resonators that without any ground plane is seems to be more suitable for wide-band
applications because stronger couplings are easier to be realized, while the common ground plane is much suitable for
narrow-band applications. If the grounding is non-perfect, it can cause extra conductor losses, resulting in a lower
unloaded quality factor of the resonator. For this project the grounding system of the layout design had been applied at the
conductor inside a substrate and grounded planes on both sides to improve the performances of the response. The
modification of the grounding system is shown in Figure 4.7.


