UNIVERSITY OF NAIROBI
FACULTY OF ENGINEERING
DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING

PROJECT: 2.4GHz ISM MICROSTRIP BANDPASS FILTER
PROJECT INDEX: PRJ 014

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A project report submitted to the Department of Electrical and Information Engineering in Partial fulfillment of the requirements of BSc. Electrical and Electronic Eng. of the University of Nairobi

Submitted on: 24th April 2015
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PROJECT NAME: 2.4 GHz ISM Microstrip Band Pass Filter

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DEDICATION

This project is dedicated to my two best friends, Elias Irungu and Felix Kithuka who served as sources of inspiration throughout my studies at the University of Nairobi.
ACKNOWLEDGEMENTS

First and foremost, I thank the almighty God for guiding me throughout my studies till the accomplishment of this project.

I am grateful to my supervisor, Dr. Wilfred Mwema for the useful guidance and suggestions throughout the project; it has been a great pleasure for me to get an opportunity to work under him.

A project of this nature could never have been attempted without reference to and inspiration from the works of others whose details are mentioned in reference section. I also acknowledge all of them.

I cannot forget the mentorship I received from Dr. Benjamin Kanake who since my childhood days, has always challenged me to pursue excellence. Many thanks to him.
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ABBREVIATIONS AND ACRONYMS

HTS- High-Temperature Superconducting.

RF- Radio Frequency

R & D- Research and Development.

EM- Electromagnetic

RC- Resistor Capacitor

BW- Bandwidth

WiMAX- Worldwide Interoperability Microwave Access

QoS- Quality of Service

TEM- Transverse Electromagnetic

FBW- Frequency Bandwidth

LPF- Low Pass Filter

HPF- High Pass Filter

BPF- Band Pass Filter

BRF- Band Reject Filter

PCB- Printed Circuit Board

CAD- Computer Aided Design

AWR- Applied Wave Research

FR4- Flame Retardant
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1. CHAPTER 1

1.1 BACKGROUND

Rapid development of wireless communications present extraordinary demand for narrow-band RF/microwave bandpass filters with high selectivity and low insertion loss. One filter with these attractive characteristics is that of quasi-elliptic function response filters with a pair of attenuation poles at finite frequencies. The capability of placing attenuation poles near the cutoff frequencies of the pass band improves the selectivity using fewer resonators. This type of filter is usually realized using waveguide cavities or dielectric-resonator-loaded cavities. However, with the advent of high-temperature superconducting (HTS) and micromachined circuit technologies, there is an increasing interest in microstrip filter structures. Two technical approaches are normally used to realize this type of filter. The first is to extract poles from both ends of a filter prototype by using shunt resonators. The size of the microstrip filter resulting from this approach may, however, be large. The second approach is to introduce a cross coupling between a pair of nonadjacent resonators. The filter employing the cross coupling generally results in a compact topology. This is obviously more attractive for those systems where size is important. It has been known that the cross coupling is more difficult to be arranged and controlled in a microstrip filter owing to its semiopen structure. It is obvious, however, that a higher degree is required for a more selective filter. In this paper I present in detail the design of highly selective microstrip bandpass filters that consist of microstrip open-loop resonators with a cross coupling that exhibit a single pair of attenuation poles at finite frequencies. A practical design technique for this class of filters, which is also different from that reported, is introduced, including tables and formulas for accurate and fast filter synthesis. The design approach enables one to use advanced full-wave EM simulators to complete the filter design, namely, to determine the physical dimensions of the filter. Two design examples of six- and eight-pole filters are demonstrated together with theoretical and experimental results.

1.2 PROJECT OBJECTIVE

This paper present design, analyze and fabricate a microstrip bandpass filter for 2.4 GHz. Basic design specifications for a bandpass filter were considered are center frequency and bandwidth. The specifications are given in the table below.

<table>
<thead>
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<th>FEATURE</th>
<th>VALUE OR TYPE</th>
</tr>
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</tr>
<tr>
<td>Bandwidth</td>
<td>10%=240Mhz</td>
</tr>
<tr>
<td>Return Loss</td>
<td>&gt;30dB</td>
</tr>
<tr>
<td>Fabrication Technology</td>
<td>microstrip</td>
</tr>
<tr>
<td>Circuit Board Material</td>
<td>FR4</td>
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<tr>
<td>Characteristic Impedance</td>
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</tbody>
</table>

### 1.3 PROJECT SCOPE

This project entails the following:

- Understand the design, fabrication and testing of 2.4 GHz Bandpass Filter developed by using Microstrip Technology.
- The results acquired through R & D process have been simulated, analyzed and verified by using parallel-coupled lines filter topology, which were later, enhanced by various value-aided software tools such as MATLAB (V 7.0), CorelDraw 12, Microwave Office (2012). For the optimal result, three samples were fabricated with the help of Microwave Office tools.
- Carry out comparative filter response analyses with the help of vector network analyzer, which gives the best choice for further analysis and development.
- Optimization of both experimental and analytical data acquired through the design, simulation, and fabrication and testing process of the bandpass filter. Subsequent results demonstrate, through verification process, that the experimental results (measured) gives more or less same performance compare analytical one (calculated).
2.0 CHAPTER TWO

2.1 LITERATURE REVIEW

2.1.1 Band Pass Filters

The cut-off frequency or $f_c$ point in a simple RC passive filter can be accurately controlled using just a single resistor in series with a non-polarized capacitor, and depending upon which way around they are connected either a low pass or a high pass filter is obtained.

One simple use for these types of Passive Filters is in audio amplifier applications or circuits such as in loudspeaker crossover filters or pre-amplifier tone controls. Sometimes it is necessary to only pass a certain range of frequencies that do not begin at 0Hz, (DC) or end at some high frequency point but are within a certain frequency band, either narrow or wide.

By connecting or “cascading” together a single Low Pass Filter circuit with a High Pass Filter circuit, we can produce another type of passive RC filter that passes a selected range or “band” of frequencies that can be either narrow or wide while attenuating all those outside of this range. This new type of passive filter arrangement produces a frequency selective filter known commonly as a Band Pass Filter or BPF for short. Using capacitors and inductors, a bandpass filter has a structure similar to the one shown in the diagram below.

![Diagram of RC implementation of the bandpass Filter](image)

Figure 1 RC implementation of the bandpass Filter

Unlike a low pass filter that only pass signals of a low frequency range or a high pass filter which pass signals of a higher frequency range, a Band Pass Filters passes signals within a certain “band” or “spread” of frequencies without distorting the input signal or introducing extra noise. This band of frequencies can be any width and is commonly known as the filters Bandwidth.
Bandwidth is commonly defined as the frequency range that exists between two specified frequency cut-off points \( f_c \), that are 3dB below the maximum center or resonant peak while attenuating or weakening the others outside of these two points.

Then for widely spread frequencies, we can simply define the term “bandwidth”, BW as being the difference between the lower cut-off frequency \( f_{c, \text{LOWER}} \) and the higher cut-off frequency \( f_{c, \text{HIGHER}} \) points. In other words, \( BW = f_H - f_L \). Clearly for a pass band filter to function correctly, the cut-off frequency of the low pass filter must be higher than the cut-off frequency for the high pass filter.

The “ideal” Band Pass Filter can also be used to isolate or filter out certain frequencies that lie within a particular band of frequencies, for example, noise cancellation. Band pass filters are known generally as second-order filters, (two-pole) because they have “two” reactive component, the capacitors, within their circuit design. One capacitor in the low pass circuit and another capacitor in the high pass circuit.

![Amplitude and phase plot for a general bandpass filter](image)
The Bode Plot or frequency response curve above shows the characteristics of the band pass filter. Here the signal is attenuated at low frequencies with the output increasing at a slope of +20dB/Decade (6dB/Octave) until the frequency reaches the “lower cut-off” point $f_L$. At this frequency the output voltage is again $1/\sqrt{2} = 70.7\%$ of the input signal value or -3dB (20 log (Vout/Vin)) of the input.

The output continues at maximum gain until it reaches the “upper cut-off” point $f_H$ where the output decreases at a rate of -20dB/Decade (6dB/Octave) attenuating any high frequency signals. The point of maximum output gain is generally the geometric mean of the two -3dB value between the lower and upper cut-off points and is called the “Centre Frequency” or “Resonant Peak” value $f_r$. This geometric mean value is calculated as being $f_r^2 = f_{(UPPER)} \times f_{(LOWER)}$.

A band pass filter is regarded as a second-order (two-pole) type filter because it has “two” reactive components within its circuit structure, then the phase angle will be twice that of the previously seen first-order filters, i.e., 180°. The phase angle of the output signal LEADS that of the input by +90° up to the center or resonant frequency, $f_r$ point where it becomes “zero” degrees (0°) or “in-phase” and then changes to LAG the input by -90° as the output frequency increases.

The upper and lower cut-off frequency points for a band pass filter can be found using the same formula as that for both the low and high pass filters, For example.

$$f_c = \frac{1}{2\pi RC} \text{Hz}$$

Then clearly, the width of the pass band of the filter can be controlled by the positioning of the two cut-off frequency points of the two filters.

Bandpass filters play a significant role in wireless communication systems. Transmitted and received signals have to be filtered at a certain center frequency with a specific bandwidth. In designing of microstrip filters, the first step is to carry out an approximated calculation based on using of concentrated components like inductors and capacitors. After getting the specifications required, we realized the filter structure with the parallel-coupled technique. Experimental verification gives comparison, how close the theoretical results and measurements look like.

The advances of telecommunication technology arising hand in hand with the market demands and governmental regulations push the invention and development of new applications in wireless communication. These new applications offer certain features in telecommunication services, which in turn offer three important items to the customers. The first is the coverage, meaning each customer must be supported with a minimal signal level of electromagnetic waves, the second is capacity that means the customer must have sufficient data rate for uploading and downloading of data, and the last is the quality of services (QoS) which guarantee the quality of
the transmission of data from the transmitter to the receiver with no error. In order to provide additional transmission capacity, a strategy would be to open certain frequency regions for new applications or systems. WiMAX (Worldwide interoperability Microwave Access) which is believed as a key application for solving many actual problems today is an example. In realization of such a system like WiMAX we need a complete new transmitter and receiver. A bandpass filter is an important component must be found in the transmitter or receiver. Bandpass filter is a passive component which is able to select signals inside a specific bandwidth at a certain center frequency and reject signals in another frequency region, especially in frequency regions, which have the potential to interfere the information signals. In designing the bandpass filter, we are faced the questions, what is the maximal loss inside the pass region, and the minimal attenuation in the reject/stop regions, and how the filter characteristics must look like in transition regions. In the process to fulfill these requirements there are several strategies taken in realization of the filters, for example, the choice of waveguide technology for the filter is preferred in respect to the minimal transmission loss (insertion loss). This strategy is still actual in satellite applications. The effort to fabricate waveguide filters prevents its application in huge amounts. As alternative, microstrip filter based on printed circuit board (PCB) offers the advantages easy and cheap in mass production with the disadvantages higher insertion losses and wider transition region. In this work we would like to give a way to conceive, design and fabricate bandpass filter for the WiMAX application at the frequency 3.2 GHz with parallel coupled microstrips as opposed to the which designed filter for wireless local area network at 5.75 GHz, and which used the composite resonators and stepped impedance resonators for filter realization.

### 2.1.2 Basics of Filter

**Transfer Function**

In Radio Frequency (RF) applications, for defining transfer function we use the scattering parameter S21. In many applications we use instead the magnitude of S21, the quadrate of S21 is preferred.

\[
|S_{21}(j\Omega)|^2 = \frac{1}{1 + \varepsilon^2 F_n^2(\Omega)}
\]

\(\varepsilon\) is the ripple constant, \(F_n(\Omega)\) filter function and \(\Omega\) is frequency variable. If the transfer function is given, the insertion loss response of the filter can calculated by

\[
L_A(\Omega) = 10 \log \frac{1}{|S_{21}(j\Omega)|^2} dB
\]

For lossless conditions, the return loss can be found by
2.1.3 Butterworth Filters

Filters designed with Butterworth approach show the maximal flat characteristics in the pass region. The figure below shows the attenuation characteristics of lowpass Butterworth filter. In the pass band region, \( f < f_c \), the attenuation of ideal low pass filter is 0 dB, good approximation must have characteristics close to zero from the frequency zero Hertz to a certain so-called cut off frequency \( f_c \). For \( f > f_c \), the ideal low pass filter attenuates the signal completely or \( LA \rightarrow \infty \).

The Butterworth approach is expected to have the attenuation factor as high as possible.

\[
L_R(\Omega) = 10 \log \left[1 - |S_{21}(j\Omega)|^2\right] dB
\]

![Graph showing the frequency response of a low pass filter](image)

The quadrate of the magnitude of the transfer function

\[
|S_{21}(j\Omega)|^2 = \frac{1}{1 + \Omega^{2n}}
\]

The figure below gives the circuit implementation of the filter by means of concentrated components like inductors (L) and capacitors (C), for the even and odd filter degree (\( n \)). The Butterworth approach for designing filter uses the condition attenuation of 3 dB at the frequency \( \Omega = \Omega_c = 1 \), so that the following equations can be used for collecting the values of L and C for the circuits.
\[ g_0 = g_{n+1} = 1 \]

\[ g_i = 2 \sin \left( \frac{(2i - 1)\pi}{2n} \right) \]

for \( i = 1 \) to \( n \).

The value of \( n \) can be determined if an additional constraint is given, for example, the filter must have minimal attenuation factor at a certain frequency.

\section*{2.1.4 Chebyshev Filter}

In practical implementation, the specification for losses in pass region can normally be higher than zero. Chebyshev approach exploits this not so strictly given specification values. It can be 0.01 dB, or 0.1 dB, or even higher values. The Chebyshev approach thereby shows certain ripples in the pass region, this can lead to better (higher) slope in the stop region. Figure 3 shows the attenuation characteristics for lowpass filter based on Chebyshev approach. The quadrature of the magnitude of the transfer function with Chebyshev approach is given by

\[ \text{Figure 4 Parameter illustration for a band pass filter} \]
\[ |S_{21}(j\Omega)|^2 = \frac{1}{1 + \varepsilon^2 T_n^2(\Omega)} \]

\( T_n(\Omega) \) is Chebyshev function type 1 with order \( n \).

\[ L_A (\text{dB}) \]

\[ \Omega_c \text{ or } f_c \]

\[ \Omega \text{ or } f \]

**Figure 5 Ideal response of a Chebyshev low pass filter**

The component values can be calculated with the following rules:

\[
g_0 = 1
\]

\[
g_i = \frac{2}{\gamma} \sin \left( \frac{2i-1}{2n} \pi \right)
\]

\[
g_i = \frac{1}{g_{i-1}} \frac{4 \sin \left( \frac{2i-1}{2n} \pi \right) \sin \left( \frac{2i-3}{2n} \pi \right)}{\gamma^2 + \sin^2 \left( \frac{(i-1)\pi}{n} \right)} \sin \left( \frac{2i-1}{2n} \pi \right)
\]

for \( i=2 \) to \( n \)

\[
g_{n+1} = \begin{cases} 
1 & \text{for odd } n \\
\coth^2 \left( \frac{\beta}{4} \right) & \text{for even } n
\end{cases}
\]

where

\[
\beta = \ln \left[ \coth \left( \frac{L_{Ax}}{17.37} \right) \right] \text{ and } \gamma = \sinh \left( \frac{\beta}{2n} \right)
\]
2.1.5 Transformation to Bandpass Filter
The previous observation was done for low pass implementation. A transformation to Bandpass is needed for getting bandpass characteristics. In the transformation, the component L will be converted to serial combinations of Ls and Cs, whereas the component C becomes parallel combination of Lp and Cp. With the cut-off frequencies $\omega_1$ and $\omega_2$ as lower and upper boundary, we can calculate the center frequency and the relative frequency bandwidth as follows

$$\omega_o = \sqrt{\omega_1 \omega_2} \quad \text{and} \quad FBW = \frac{\omega_2 - \omega_1}{\omega_o}$$

And the values for the new components are

$$L_s = \left( \frac{1}{FBW \cdot \omega_o} \right) Z_o \cdot g$$

$$C_s = \left( \frac{FBW}{\omega_o} \right) \left( \frac{1}{Z_o \cdot g} \right)$$

for the serial combination, and

$$C_p = \left( \frac{1}{FBW \cdot \omega_o} \right) g \frac{1}{Z_o}$$

$$L_p = \left( \frac{FBW}{\omega_o} \right) \frac{Z_o}{g}$$

for the parallel combination.

$Z_o$ is the value of the load impedance, normally set to 50 $\Omega$.

2.2 FILTER REALIZATION WITH MICROSTRIP TECHNOLOGY

2.2.1 Microstrip Transmission Line
Microstrip transmission line is the most used planar transmission line in Radio frequency (RF) applications [5]. The planar configuration can be achieved by several ways, for example with the photolithography process or thin-film and thick film technology. As other transmission line in RF applications, microstrip can also be exploited for designing certain components, like filter, coupler, transformer or power divider. If a microstrip transmission line, as depicted in Fig. 4, is used for transport of wave with relative low frequency, the wave type propagating in this
transmission line is a quasi-TEM wave. This is the fundamental mode in the microstrip transmission line.

Figure 6 Structure of a microstrip Transmission line

The width of the strip $W$ together with the dielectric constant and the thickness of the substrate determines the characteristic impedance $Z_0$ of the line.

2.2.2 Designing Bandpass Filter

The figure below shows the filter structure observed in this work. This filter type is known as parallel-coupled filter. The strips are arranged parallel close to each other, so that they are coupled with certain coupling factors. We use the following equations for designing the parallel-coupled filter

$$\frac{J_{01}}{Y_o} = \sqrt{\frac{\pi FBW}{2g_0g_1}}$$

$$\frac{J_{j,j+1}}{Y_o} = \frac{\pi FBW}{2} \frac{1}{\sqrt{g_j g_{j+1}}}$$

for $j=1$ to $n=1$

$$\frac{J_{n,n+1}}{Y_o} = \sqrt{\frac{\pi FBW}{2g_ng_{n+1}}}$$
\( g_0, g_1, \ldots, g_n \) can be taken from table, FBW is the relative bandwidth as explained before, \( J_{j,j+1} \) is the characteristic admittance of \( J \) inverter and \( Y_0 \) is the characteristic admittance of the connecting transmission line. With the data of characteristic admittance of the inverter, we can calculate the characteristic impedances of even-mode and odd-mode of the parallel-coupled microstrip transmission line, as follows

\[
(Z_{0e})_{j,j+1} = \frac{1}{Y_0} \left[ 1 + \frac{J_{j,j+1}}{Y_0} + \left( \frac{J_{j,j+1}}{Y_0} \right)^2 \right]
\]

for \( j = 0 \) to \( n \), and

\[
(Z_{0o})_{j,j+1} = \frac{1}{Y_0} \left[ 1 - \frac{J_{j,j+1}}{Y_0} + \left( \frac{J_{j,j+1}}{Y_0} \right)^2 \right]
\]

for \( j = 0 \) to \( n \).
3.0 CHAPTER 3

3.1 DESIGN OF THE 2.4GHz MICROSTRIP BANDPASS FILTER

3.1.1 The Microstrip
The microstrip belongs to the group of parallel-plate transmission lines and consists of a single ground plane and an open strip conductor separated by a dielectric substrate. Microstrip lines are the most commonly used form of transmission lines for microwave integrated circuits. Also, microstrips are used as circuit components for filters, phase shifters, couplers, resonators and antennas.

![Diagram of a microstrip transmission line](image)

The electromagnetic field in the microstrip line is not confined only to the dielectric and because of the fringing; the effective relative permittivity $\varepsilon_{\text{eff}}$ is less than the relative permittivity $\varepsilon_r$ of the substrate. The electromagnetic waves in microstrip propagate in TEM (transverse electric magnetic) mode, which is characterized by electric and magnetic fields that exist only in the plane perpendicular to the axis of the wave propagation.

3.1.2 Parallel Couple Microstrip Lines
As in the case of a single microstrip line, a parallel-coupled microstrip arrangement is also a TEM-mode system. The relative polarities of the voltages on the coupled microstrip lines at any specific plane along the structure and at any specific time will be the same or opposite resulting...
in two different modes of field distribution, namely the even-mode and the odd mode. These modes are illustrated in the figures below.

![Even and Odd modes for the microstrip line](image)

Figure 9 Even and Odd modes for the microstrip line

The two field distributions result in even-mode and odd-mode characteristic impedances denoted by $Z_{0e}$ and $Z_{0o}$. These characteristic impedances are major parameters in design procedures. The complete behavior of the parallel-coupled microstrip structure can be obtained by superposition of the effects due to these two modes.

### 3.1.3 The Filter

A filter is a device or substance that passes electric currents at certain frequencies or frequency ranges while preventing the passage of others. Based on the frequencies they pass, the filters are classified as low pass filters (LPF), high pass filters (HPF), bandpass filters (BPF) and bandreject filters (BRF). These filter types are best explained based on the characteristics of a normalized low pass filter because characteristics of other filter types can be related to the low pass filter characteristics. The ideal low pass filter is characterized by zero loss and zero ripples in the passband, an infinite attenuation slope at cutoff frequency and infinite attenuation in the stopband.

### 3.2 METHODOLOGY

Basic design specifications for a bandpass filter were considered are center frequency and bandwidth. The other specifications are given in Table 1. above. For this research a center frequency of 2.4 GHz, which corresponds to the free-space wavelength of 12.5 cm, was chosen for hand-based dimensions fabrication. With using formula related to calculate dimension of parallel couple filter, found $L$(length),$W$(width), and $S$(spice) as shown in Table II[3]. The filter designed was fabricated with the aid of Correl Draw 12 and CAD tools to print exact dimension on PCB for simulation purpose. The filter characteristics were measured. As the results of
literature review recommendations, +/- 10% bandwidth, which corresponds to 240 MHz at 2.4 GHz center frequencies, was chosen for further research and development process. The choice of the parallel-coupled lines filter has been explained analytically with the help of Microwave Office 2004 to aid design process for the evaluation of calculated result and simulation frequency response.

### 3.3 DESIGN AND DEVELOPMENT OF A MICROSTRIP FILTER

In this section, a sample ultra-wideband microstrip filter design and development is presented. Filter details including circuit model, simulations, optimizations, layout creation, manufacturing, testing and troubleshooting are explained.

The essential design flow in this study is given in the flow chart below

![Flow chart for the implementation of the filter](image)
After determining the prototype and specifications for the filter, the circuit simulation optimizations are done by using AWR Microwave Office. EM Simulation is followed by using the circuit simulation. Sonnet EM Simulation and CST EM Simulation Tools are used for the EM Simulation to have accurate results with a good comparison performance. A tolerance analysis is also done using the simulation tools. Then filter layout is generated and fabricated using the circuit milling machine. Filter response is measured using a vector network analyzer (VNA). Once it is observed that the filter basically is functioning near the specifications, a minor troubleshooting is applied to tune the filter. The filter design in this study starts with an ideal model composed of quarter wavelength shorted stubs separated with half wavelength inverters. This topology has been adopted for its simple structure. In this thesis, design and manufacturing of an ultra-wideband microstrip line filter covering the 2.4Ghz strip is considered. The ideal electrical model for the filter is based on half wavelength separated shorted stub resonators using distributed microstrip lines.

The design specifications for this filter as follows:

- -30 dB rejection at 2.1 GHz
- Return Loss better than -10 dB within the band

The electrical design prototype of the filter is shown in Fig.3.3. Figure 3.3: The design prototype of the filter

3.3.1 Design Model

The structure and dimension of microstrip base on calculation as follows

![Figure 11 Structure of couple line band pass filter microstrip N= 3](image-url)
The dimensions for the above microstrips were calculated using the TX line feature on AWR 2012.

Figure 12 Screen Capture of a Microstrip Line analyzer
The dimensions for the microstrip transmission line can also be obtained from the Android App shown in the figure below.

Figure 13 Screen Capture of the RF microstrip Transmission line App
Table 2 Microstrip Dimensions

<table>
<thead>
<tr>
<th>Section</th>
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<th>1</th>
<th>2</th>
<th>3</th>
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</thead>
<tbody>
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<td>w(mm)</td>
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<td>1.68</td>
<td>2.48</td>
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</tr>
<tr>
<td>S(mm)</td>
<td>-</td>
<td>0.19</td>
<td>1.21</td>
<td>0.85</td>
<td>0.46</td>
</tr>
<tr>
<td>L(mm)</td>
<td>16.51</td>
<td>17.04</td>
<td>16.53</td>
<td>16.53</td>
<td>17.64</td>
</tr>
</tbody>
</table>

The filter schematic as designed on AWR Design Environment is as shown in the diagram below. The dimensions of the various sections were obtained from the table above.

Figure 14 Design of the 2.4GHz Band Pass Filter on AWR Design Environment
3.4 EXPECTED RESULTS

The graph for the variation of the Return Loss is as shown below.

The tuned results for the Return Loss are as shown in the diagram below.
Figure 16 Tuned Return Loss

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Frequency centre ($f_c$)</th>
<th>Band Width (BW)</th>
<th>Return Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specifications</td>
<td>2.4 GHz</td>
<td>240 MHz at 3 dB pass band</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Simulation result “Microwave Office 2004”</td>
<td>2.4 GHz</td>
<td>500Hz at 3 dB at pass band</td>
<td>22.4</td>
</tr>
<tr>
<td>Test Result (sample 1 the best)</td>
<td>2.4 GHz</td>
<td>260 MHz at 3 dB pass band</td>
<td>21.9</td>
</tr>
<tr>
<td>Differences between simulation and result (%)</td>
<td>0 %</td>
<td>48 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Differences between specs and result (%)</td>
<td>0 %</td>
<td>8 %</td>
<td>Better</td>
</tr>
</tbody>
</table>

The complete filter after fabrication is as shown in the diagram below.

Figure 17 Final BandPass Filter
4. CHAPTER 4

4.1 RESULT AND DISCUSSION

The following results were obtained for the Filter designed using the parameters above.

![Attenuation and Return Loss](image)

Figure 18 Attenuation and Return Loss
The following value was obtained for the bandwidth at an input power of 30dB

![Attenuation and Power](image)

Figure 19 Attenuation and Power

4.2 CONCLUSION

It is hoped that this design examples show how I used many different design resources. To create these filter and coupler circuits, the experience of several other works was combined with published data, advanced circuit theory simulation, EM analysis and, finally, fabrication and measurement. Each step in the process contributed to the overall design success. Designing of bandpass filter with Butterworth approach in combination with concentrated components, i.e. inductors and capacitors and its computational verification in form of parallel-coupled microstrip lines with the program AWR Design Environment give very good filter characteristics at the center frequency 2.4 GHz with frequency bandwidth of about 100 MHz as required at the specification stage. At the center frequency the insertion loss and reflection factor has the values about -2 dB and better than -15 dB, respectively. The measurement gives also very good filter characteristics at the frequency 2.4 GHz, however with larger insertion loss of about -7.5 dB and smaller bandwidth of about 50 MHz. This larger loss originates likely from losses of the coaxial connectors and their poor contacts to the microstrip line.
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