Design a Butterworth Band-pass Filter (BBPF) for GPS Application

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***Abstract*—This paper presents the design of a Butterworth microstrip parallel couple band-pass filter (BBPF) for GPS application. Butterworth approach was used in designing the filter and the simulation was carried out using CST simulation software. The operating frequency range from 1559MHz to 1610MHz with the cut-off frequency 1575MHz with the consideration of 24MHz bandwidth It wil demonstrate the third order of the Butterworth elements. The specified pass band insertion loss must not exceed 3dB while the pass band return loss was to be more than 20dB. The filter were fabricated on RT/Duroid 4350B having a relative permittivity of 3.48, and substrate thickness 1.542mm respectively. The filters characteristic were then measured using Rhodes&Schwarz ZVR-40 vector network analyzer. The simulation result show a good agreement.**

Keywords—**Parallel Couple band-pass filter, Computer Simulation Technology (CST), Microstrip, Return loss, Insertion loss**

I. INTRODUCTION

Microwave filters [1]-[2] are two-port networks used in an electronic system capable of allowing transmission of signals over the pass-band and rejecting unwanted harmonics over the stop-band. Different kinds of approximations, like Butterworth, Chebyshev [3] and Elliptic function [4] have been proposed and widely used as models for microwave-filter synthesis.Microwave and RF filters are widely used in all these systems in order to discriminate between wanted and unwanted signal frequencies [5].

There are various filter types that used in communication systems classified as low-pass filter, high-pass filter, band-pass filter, and also band-stop filter. Band-pass filter is widely used in telecommunication system, be it in receiving or transmitting devices, to filter out unwanted frequency [6].

Band-pass filter has the property that one band of frequency is transmitted while two band of the frequencies namely those below and above the pass-band are blocked. Fig 1 shows a basic structure of microstrip line [7]

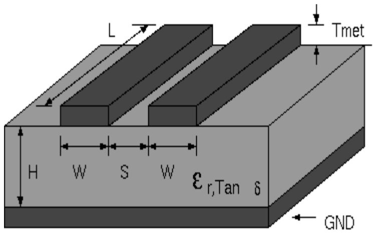

Fig.1: Basic structure microstrip line.

These filters have the advantage of good harmonic suppression, but are still too large to be inserted into commercial transceiver systems. The quarter-wavelength ceramic combline filter, using a high dielectric constant material, is another type of miniaturized bandpass filter. Nevertheless, the electrical length of the transmission line itself is not reduced in this combline filter [7].

A .Parallel Couple Filter Theory

Parallel Coupled line structure is a technique to design the filter at microwave frequencies.The resonator are positioned parallel to each other ,so that the adjacent resonators are coupled along a length equal to the quarter-wavelenght of the center frequency of the filter.Parallel coupled microstrip band-pass filters are small in size and easy to fabricate due to the absence of the short circuit. The disadvantages of this filters are parasitics bandwidths, the difficulty of obtaining a narrow band, and the radiation from open ends [8].Two microstrip line were used as the main block of parallel coupled line construction.

The parameters of the Butterworth Parallel coupled line filter consists of the length ,*l* and the width of the coupled lines known as space gap, *s*.Most coupled line filter design involved gap between coupled lines,where the value can be several thousand of inch wide. Physical parameters that are affecting to the filter performance are coupled line width, gaps between coupled lines,trace thickness,ground plane construction and the dielectric constant of the substrate material[5].The dielectric constant tolenrence on the substrate material has the most dramatic effect on the filter performance.It shifts the filter pass-band, especially in narrow bandwidth circuits.The spacing of the ground planes affects filter bandwidth and pass-band insertion loss.

B. GPS overview

The Global Positioning System (GPS) is a satellite-based navigation system made up of a network of 24 satellites placed into orbit by the U.S. Department of Defense. GPS was originally intended for military applications, but in the 1980s, the government made the system available for civilian use. GPS works in any weather conditions, anywhere in the world, 24 hours a day [9]

GPS satellites transmit two low power radio signals, designated L1 and L2. Civilian GPS uses the L1 frequency of 1575.42 MHz in the UHF band. [10] The signals travel by line of sight, meaning they will pass through clouds, glass and plastic but will not go through most solid objects such as buildings and mountains.

The 24 satellites that make up the GPS space segment are orbiting the earth about 12,000 miles above us. They are constantly moving, making two complete orbits in less than 24 hours. These satellites are travelling at speeds of roughly 7,000 miles an hour.GPS satellites are powered by solar energy. They have backup batteries onboard to keep them running in the event of a solar eclipse, when there's no solar power.

II. SCOPE OF WORKS

The work was limited to a Butterworth band-pass filter incorporated parallel couple lines using commercial simulation software; *CST Microwave Studio*. Band-pass filter was designed based on the following specification:

Table1
Band-Pass Filter Design Specifications

Centre frequency, f_0	1575MHz
High cut-off frequency, f_H	1559MHz
Low cut-off frequency, f_L	1660MHz
Bandwidth	24 MHz
Filter order, n	3^{rd} order

The simulation was carried out to determine the optimum values for the length, *l*, width, *w* and the gaps, *s* of BBPF. Finally, to produce a prototype Butterworth band-pass filters on the RT Roger Duroid 4350B substrate with dielectric 3.48 for original dimension

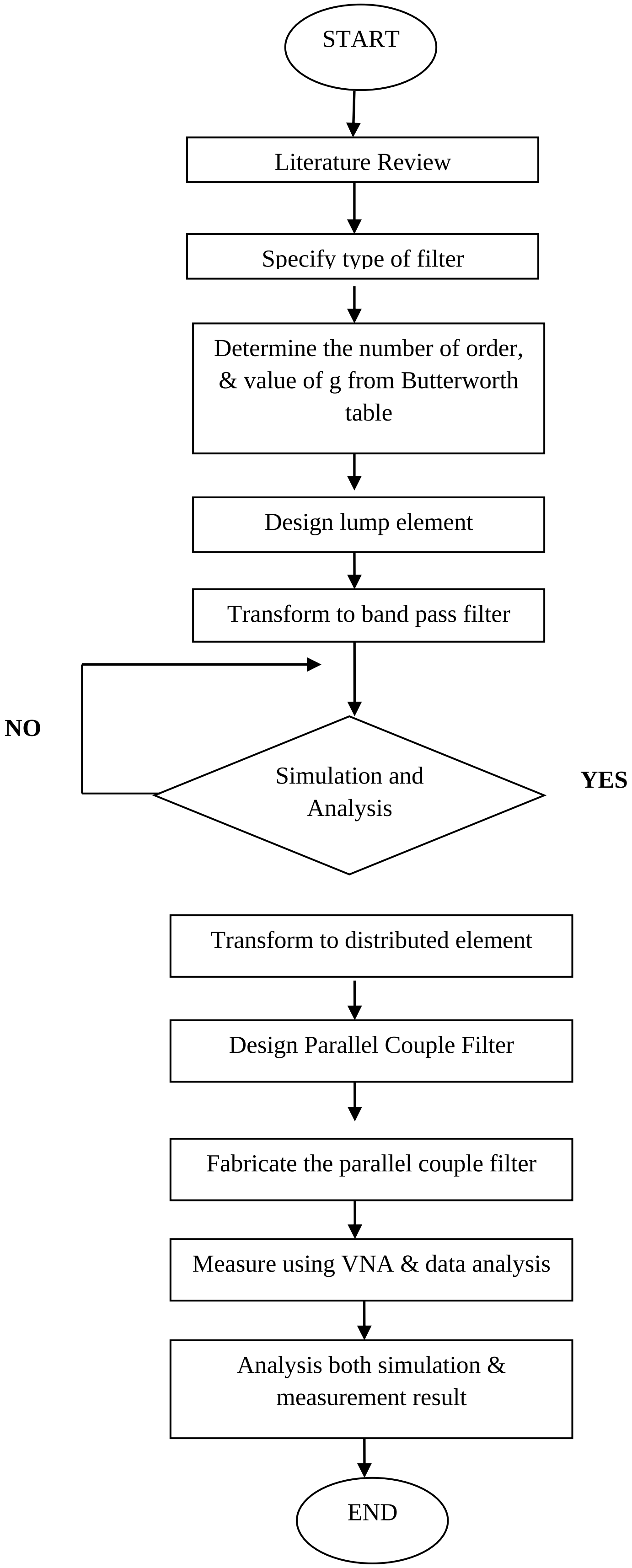

Fig 2: Design Flowchart

III. METHODOLOGY

Fig.2 shows the flowchart all the works involved in designing the filter. Literature review was done to obtain information of Butterworth band pass filter. Computer Aided Design (CAD) is used to design, simulate and evaluate the response of the band-pass filter at 1575MHz.

A. *Design Procedure*

The design of a filter usually starts with a set of parameters that will satisfy the requirements of an application. These steps are call specification. Table 2 shows the specification of RT/Duroid 4350B substrate used in the project.

Table 2
RT/Duroid 4350B Substrate Properties

Microstrip properties

Dielectric constant, ε	3.48
Height	1.542mm
Loss tangent	0.0001
Roughness	0.0000mm

Microstrip conductor

Thickness	0.035mm
Resistivity	1.000 rel Au

The first step to design a filter is to determine the specifications of the filter such as the order of the filter (n) and operating frequency range. The filter is designed with n=3, which represent the number of the filter. Table 3 is used to obtain all of the element values, which show the element values from g_0 to g_4 for Butterworth response.

Table 3
Butterworth filter prototype

g_0	g_1	g_2	g_3	g_4
1.000	1.0000	2.0000	1.0000	1.000

In the prototype table, given here some of the more important transfer function g-value listings. Each row is set of g-values for a given up to third order. The value obtained from the table is the normalized value with respect to 50Ω impedance. Based on the prototype values, the values are denormalized to obtain the actual value by using the following formula (1), (2) and (3).

$$C_{act} = \frac{g}{R_G} \tag{1}$$

$$L_{act} = gR_G \tag{2}$$

$$R_G = 50\Omega \tag{3}$$

In designing microstrip parallel couple band-pass filter, lumped elements of band-pass filter have to be converted into distributed element.. The fractional bandwidth of the pass-band can be obtained by using the following equation in (4). The purpose of the fractional bandwidth calculation is allow us to compute parameters such as first coupler, intermediate coupler and the final coupler which is referring to equation (5) to (7) respectively.

Fractional bandwidth

$$\Delta = \frac{\omega_U - \omega_L}{\omega_o} \tag{4}$$

First coupler

$$Z_0 J_{0,1} = \sqrt{\frac{\Delta\pi}{2g_o g_1}} \tag{5}$$

Intermediate coupler

$$Z_0 J_{i,j+1} = \frac{\Delta\pi}{2\sqrt{g_i g_{i+1}}} \tag{6}$$

Final coupler

$$Z_0 J_{n,n+1} = \sqrt{\frac{\Delta\pi}{2g_n g_{n+1}}} \tag{7}$$

After calculating the impedance inverter values, the next step is to calculate even and odd characteristic line impedance. The formulas for both even and odd line impedance are calculated by using equation (8) and (9) where Z_o= 50Ω. The overall circuit performance is the multiplying of square root due to both even-mode and odd-mode excitation. The impedance parameters are as follows equation (10).

For even (Z_{oe})

$$Z_{oe\ i,i+1} = Z_o\left[1 + Z_o J_{i,i+1} + \left(Z_o J_{i,i+1}\right)\right] \tag{8}$$

For odd (Z_{oo})

$$Z_{oo\ i,i+1} = Z_o\left[1 - Z_o J_{i,i+1} + \left(Z_o J_{i,i+1}\right)\right] \tag{9}$$

$$(Z_O)_{i,i+1} = \sqrt{(Z_{oe})_{i,i+1} x (Z_{oo})_{i,i+1}} \tag{10}$$

Coupling factor in dB

$$C_{i.i+1} = 20\log\frac{Z_{oe\,i,i+1}-Z_{oo\,i,i+1}}{Z_{oe\,i,i+1}+Z_{oo\,i,i+1}} \qquad (11)$$

Finally, all of the value obtained is inserted into *LineCalc* to obtain the width, length, and spacing of the filter. Table 4 below summarized the value of Z_{oe} , Z_{oo} , Z_O and coupling factor, C.

Table 4: Calculated value for characteristic impedance and coupling factor

N	Z_{oe} (Ω)	Z_{oo} (Ω)
1	59.009	43.421
2	50.874	49.155
3	59.009	43.421

B. CAD simulation

The filter is then simulated using *CST Microwave Studio* and it is being optimized to achieve the best response. The 3D layout of the parallel couple filter is illustrated in Fig.4 based on distributed element dimension.

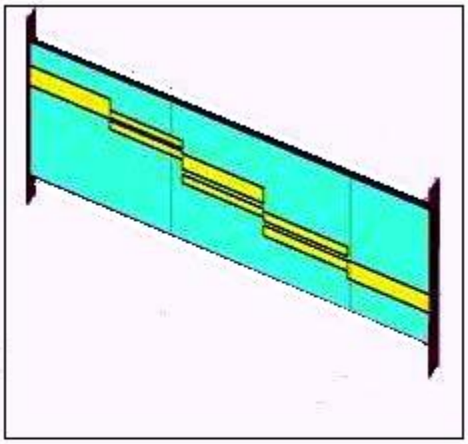

Fig.4: Butterworth Parallel Couple band-pass filter physical layout

To obtain the best layout of the filter before it meet the specification, a lot of optimization process had to be done. After the optimization process, filter layout is realized using *AutoCAD 2008* and then fabricated on RT Rogers Duroid 4350B. The final dimension of the filter layout is shown in Fig.5.

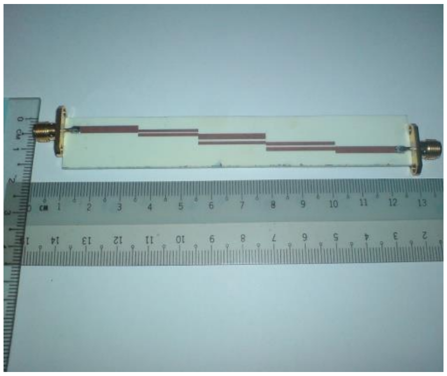

Fig.5: Fabricated Parallel Couple Band-pass filter

IV Result and Discussion

Table 5: Comparison between simulation and measurement result

Parameter	Simulated results	Measured results	%Difference
Center frequency(f_O)	1519.2MHz	1840MHz	21.1164%
High cut-off frequency(f_H)	2046.7MHz	2202MHz	7.5878%
Low cut-off frequency(f_L)	1181.3MHz	1760MHz	48.9884%
Insertion loss(S_{21})	-1.7686858dB	-1.270dB	28.1952%
Return loss (S_{11})	-23.798268dB	-18.520dB	22.1792%

To examine the filter performances, experimental measurements are carried out by using Rhodes&Schwarz ZVR-40 vector network analyzer. Measured filter responses are presented and compared with those predicted by simulations. Table 5 shows the value between simulation and measurement process while Fig. 6 and Fig 7 show comparison between S11 and S21 measurement and simulation of the proposed prototype. From these curves, it can be noted that an acceptable difference between simulations and the experimental results is observed.

The passband insertion loss, S_{21}, is approximately -1.7686858dB for simulated result and -1.270dB for measured results. Although there are differences in terms of measured & simulated pass band insertion loss values, the results for measurement show some improvement compared to the simulation results. For passband return loss, S_{11}, the result for the measurement and simulation are -18.520dB and -23.798268dB respectively. Even though the measured result is less than its specification which is supposed to be greater than 20dB, the value still can be accepted.

Also from Fig. 7, it is shown that the measured response for center frequency is shifted to 1840 MHz compared to simulation which is 1519.2 MHz. All of the error occurrences during measurement are due to several factors and losses, for instance conductor loss. In microstrip line, this loss refers to the characteristics impedance design in prototype, which increases as the resistance of narrow conductor strips is high. Imperfection of design and fabrication process also has potential in resulting to the difference between measurement and simulation results.

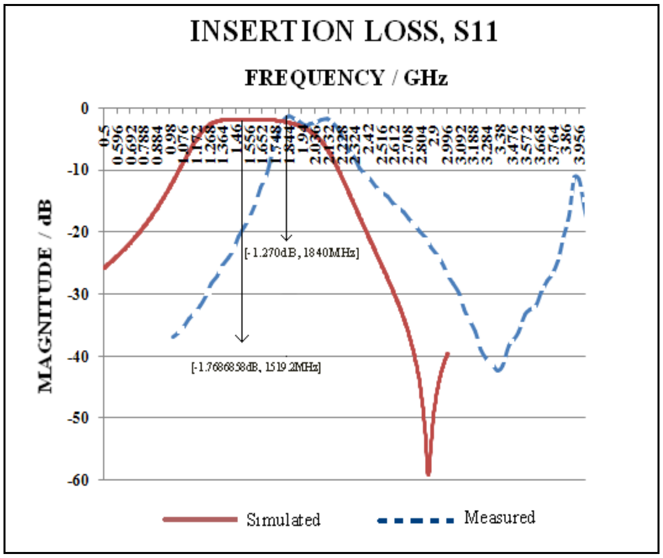

Fig.6: Comparison between S11 measurement and simulation

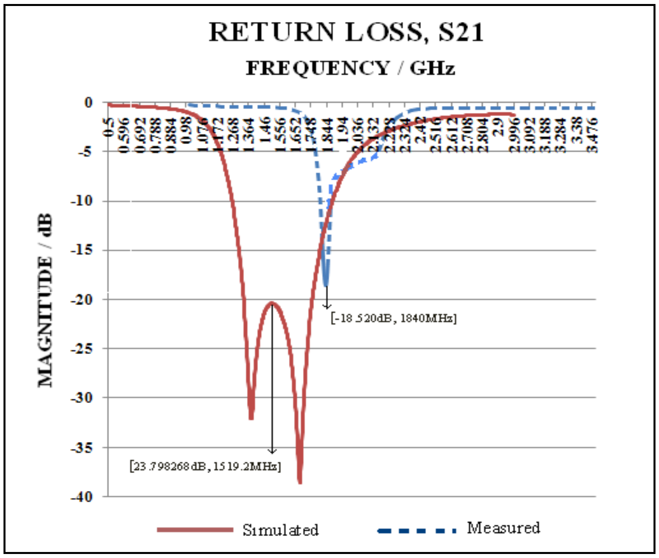

Figure 7: Comparison between S21 measurement and simulation

V. CONCLUSION

The objective of this project in terms of designing and measuring the characteristic of microstrip parallel couple lines has been succeeded. Both theoretical and experimental performances of the filter have been presented, and even there exists some difference between measured and simulated results, these differences are still acceptable. Careless handling of microstrip is capable to cause strain and stress which modify the performance of the filter.

VI. FUTURE RECOMMENDATION

For further development of this filter, it is recommended the fabrication process should be done carefully to avoid more losses on microstrip during measurement process. This filter also can be designed on different substrate with different properties and structure to get the best results. In addition, for future design, the bandwidth of the filter should be accounted for when designing this type of filter.

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