Butterworth Low-pass Filter Design

Ismahalili Bin Ishak
Faculty of Electrical Engineering
University Technology Mara,
40450, Shah Alam, Malaysia.
Email: legolas_alex85@yahoo.com

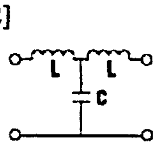
Abstract —**This work higlighted on the development carried out on miniaturized intergrated filter at center frequency of 10GHz. The design, development and fabrication of Butterworth low-pass filter are accomplished for Rogers Duroids to observe the effect of low-k material.The results has revealed that the simulation and measured is comparable as expected. In contrast, the Butterworth low-pass filter for high-k material is focused on the design and the simulation using CAD tools. The result has shown that the physical shape is minimized, the center frequency is reduced to 2.5GHz.**

I. INTRODUCTION

Filters are used in applications such as channel separation in frequency division multiplexing (FDM), for the removal of harmonics in oscillators or amplifiers, noise reduction and to reject signals at particular frequencies in bandstop filter applications[1]. Butterworth is the types of filter are commonly used in microwave filters. Microstrip, waveguide and coaxial are the types of circuit used in microwave filter design.

Low -pass filter is filter that passes at low frequency signal but attenuates(reduces of amplitudes)signal with frequency higher than the cutoff frequency. Concept of low pass filter exists in many different form including electronic circuits, digital algorithms for smoothing set data and acoustic barrier. An ideal low pass filter completely eliminates all frequencies above the cutoff frequency and can be realized mathematically by multiplying a signal by the rectangular function in the frequency domain.

Low -pass filters using LC components are arranged in ether a pi or T network as shown in Fig 1 respectively. Tee network low pass filter has one capacitor component to ground and inductor component on either side connected in series.[2]



Tee low pass circuit

Fig.1 The circuit representation of Tee low pass cicuit

At RF frequencies and the lower end of the microwave frequency band, filters have been realized using lumped elements Lumped-element filters can be implemented easily, and using currently available surface-mounted components one can meet size and cost targets in high-volume production. it is not possible to realize narrowband filters using MIC or MMIC technologies for some wireless applications.[3]

In designing low pass filter, bandwidth and physical shape are among the parameters that need to be considered. Capacitor is one of the element uses in designing filter and it has capability to store energy [3]. Performance of low pass filter depends on capacitor. The filter performance is differed if using low-k and high-k capacitor. This is because dielectric constant changes with frequency range. Therefore, the introduction of high-k capacitor in low pass filter design may provide some impact to the performance of the filter especially to physical shape and bandwidth.

In this paper, frequency range of 20GHz is used to observe the performance and physical shape of Butterworth low -pass filter on Rogers Duroid and high-k dielectric. CAD tools are employed to design and simulate the low -pass filter for both materials. The result has shown the physical change and the perfomance that affect the low pass filter when different dielectric material are applied in the design.

II. SCOPE OF WORK AND OBJECTIVES

In this work, low pass filter will be designed based on the following specifications:
Number of elements, n = 3
Center frequency = 10GHz
Cut off in dB = 3dB
Then, the design will be analyzed based on computer simulation, fabrication and measurement for Rogers Duroid. For high k, the design will be analyzed based on computer simulation only.

III. LOW-PASS FILTER THEORY

In order to reduce losses due to skin effect, the element were transformed into short and open circuit stubs[4]. Using equations, a parallel capacitor C, can be transformed into a low impedance open circuit stub of length l :

$$l = \frac{\lambda_L \omega_c C Z_L}{2\pi}$$

While a shunt inductor L can be represented by a high impedance short circuit stub l

$$l = \frac{\lambda_h \omega_c L}{2\pi Z_h}$$

where ω_c is the cut off frequency in radians, while Z_L and Z_h are the lowest and the highest realizable characteristic impedance in the medium respectively and λ_L and λ_h are the corresponding wavelengths related to free space wavelength

$$\lambda_h = \lambda_L = \frac{\lambda_o}{\sqrt{\varepsilon_{reff}}}$$

ε_{reff} is the effective dielectric constant and can be obtained from *LineCalc* in *Libra.*

IV. DESIGN TECHNIQUES

Fig.2 shows the flow chart for the work of this project. Literature review is done to obtained information of Butterworth low-pass filter in low-k material. CAD tools is used to simulated the design and obtain the result. Then the material is replaced in the design by changing the value for dielectric constant. Finally, the result is analyzed.

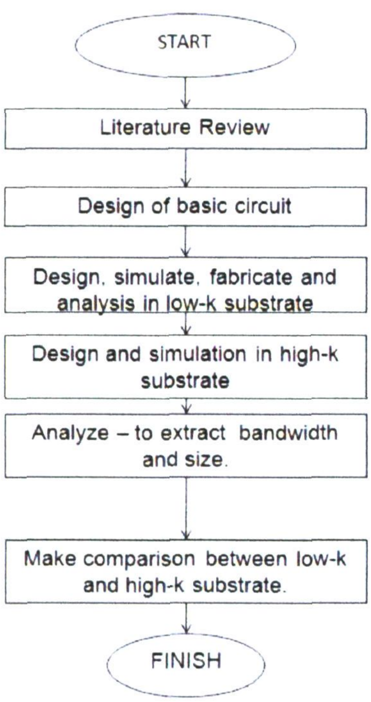


Fig. 2 Flow chart the process design

V. CAD SIMULATIONS

Low pass filter is designed using CAD tools to acquire the expected result based on the specification given in Sec. II. All the simulations are using Genesys and CST software.

A. Low pass filter

Genesys software is used to design the low-pass filter using the available synthesis tool. In this design, two layout is constructed based on the effect of the feeder line. The values from the lumped elements in the synthesis tool then is converted to distributed element which include Rogers Duroid as the substrate. Relative dielectric constant (ϵ_r) for Rogers Duroid is 2.33.

a. Without feeder line 50Ω

The design without feeder is not accounted for the 50Ω matching. As shown in Fig.3 is the lumped element representation of the low-pass filter without feeder. The conversion of the distributed of the low-pass filter using synthesis tool is shown in Fig. 4 and Fig.5 illustrates the final layout of the design.

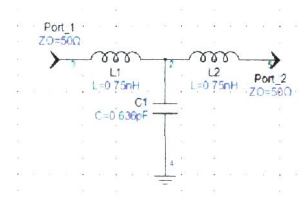


Fig. 3 Lumped elements circuct for low pass filter without feeder line 50Ω

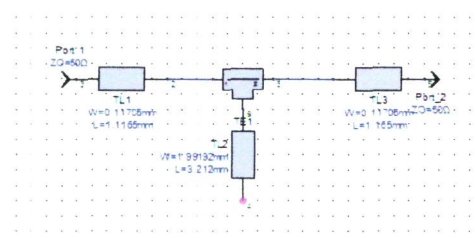


Fig. 4 Distributed element for low pass filter without feeder line 50Ω

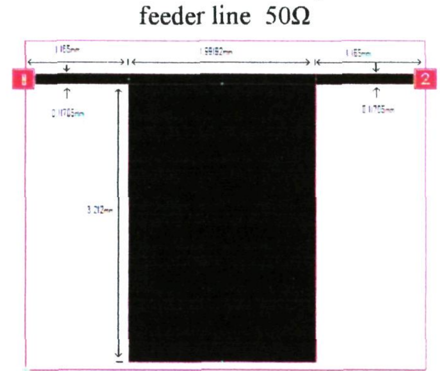


Fig. 5 Layout and dimension of low-pass filter without feeder line 50Ω

b. With feeder line 50Ω

The purpose of adding feeder line 50Ω to the design is to match the SMA connector to the transmission line of the microstrip for VNA measurement. Fig.6 depicts the distributed element of the lowpass filter with feeder line 50Ω .

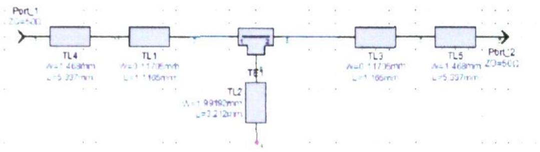


Fig.6 After convert to distributed elements by adding feeder 50Ω.

Similar technique as mentioned in sec (a:without feeder line 50Ω) is applied to determine the lumped element value for low-pass filter with feeder line 50Ω. However, the feeder line 50Ω is obtained from *LineCalc* in *Libra*. The value of the distributed elements for feeder line 50Ω at 10GHz is **width = 1.468mm** and **length = 5.337mm**. Fig.7 shows the overall layout and the dimension of thelow pass filter with feeder line 50Ω

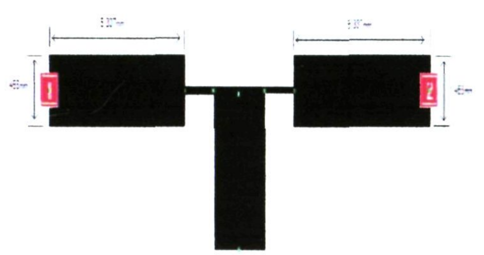


Fig.7 Dimension after adding feeder 50Ω

B. High k material

Similar specification is done in designing Butterworth low-pass filter with high-k material. The result has shown that the physical shape is minimized by 90% as depicted in Fig.8.

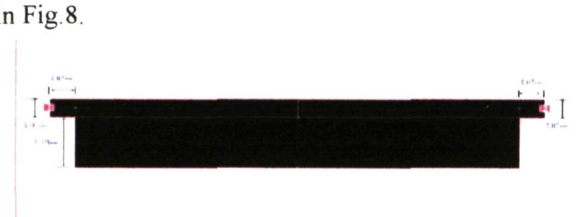


Fig.8 Layout and dimension reduce by 90%

Table 1 shows that dimension is changed from low-k to high-k material. The reduction on physical shape is changed on the length of distributed elements. It is because the value for width representing value for characteristic impedance, Zo.

Low-k dimension	High-k dimension (reduce by 90%)
W=0.11705mm L=1.1165mm	W=0.11705mm L=0.117mm
W=1.99192mm L=3.212mm	W=1.99192mm L=0.321mm
W=0.11705mm L=1.1165mm	W=0.11705mm L=0.117 mm

Table 1 Physical dimension for high-k and low-k material.

Fig.9 shows the simulation result between Genesys and CST using high-k material. The CST simulation exhibits that the output response has more ripple and spike, on the other hand the output response is behaved similarly to low-pass filter. It is because of inaccurate model and also using different dielectric constants. Conversely, both simulations demonstrate the low pass response. On the contrary, Genesys and CST produce different f_c of 8.5GHz and 2.2GHz respectively as well as the cut-off(dB) of -3dB and -9dB.

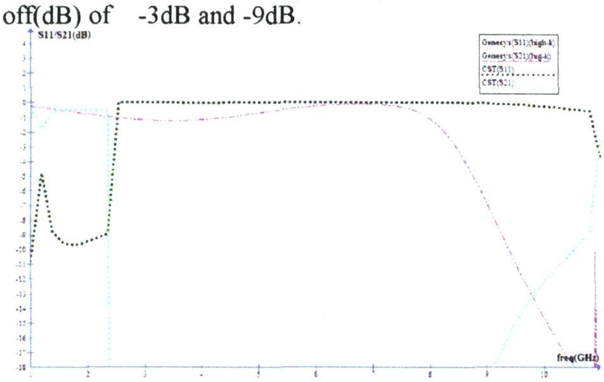


Fig.9 Output response from Genesys and CST simulation using high-k material.

VI. FABRICATION AND RESULT

The two design using Roger Duroid are fabricated based on the dimension from Genesys and CST simualtion. Then the measurement is demonstrated using vector netwok analyzer (VNA) to verify the prototypes. The VNA is calibrated using standard calibration[5].

a. Low pass filter without feeder line 50Ω

Fig.10 illustrate the prototype of low pass filter without feeder line 50Ω. The result of the measurement is tabulated in Table 2 in addition to simulation result.

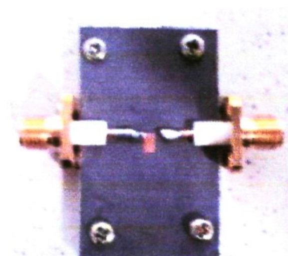


Fig.10 Prototype of low-pass filter without 50 Ω feeder

	Simulation		Measured(VNA)
	Genesys	**CST**	
Center frequency, fc(GHz)	11.8	10.8	Cannot be read
Cut-off (dB)	-3.3	-3.05	Cannot be read

Table 2 Result in fc and cut-off(dB).

The output response of the simulation and the measurement is illustrated in Fig.11.

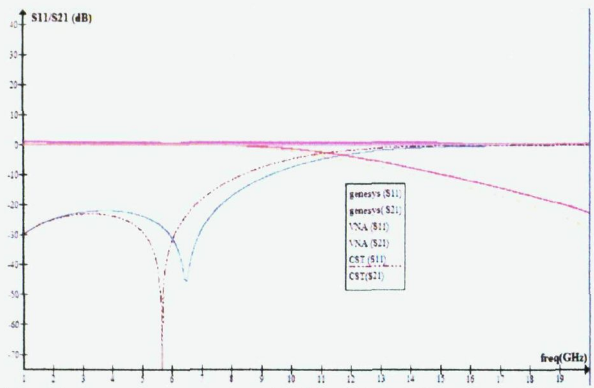


Fig. 11 Output response obtained from Genesys, CST and VNA measurement.

b. Low pass filter with feeder line 50Ω

Prototype of low-pass filter with feeder line 50Ω is depicted in Fig. 12. Measurement and simulation results is tabulated in Table 4.

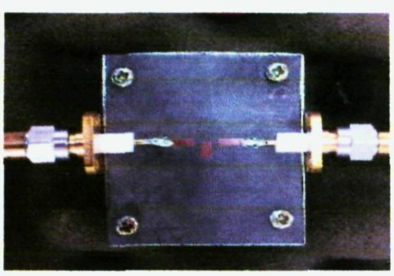


Fig.12 Prototype of low-pass filter with 50Ω feeder.

	Simulation		Measured(VNA)
	Genesys	**CST**	
Center frequency, fc(GHz)	11.6	10.8	10.2
Cut-off(dB)	-3.3	-3	-4.2

Table 3 Result in fc and cut-off(dB) after adding feeder 50Ω.

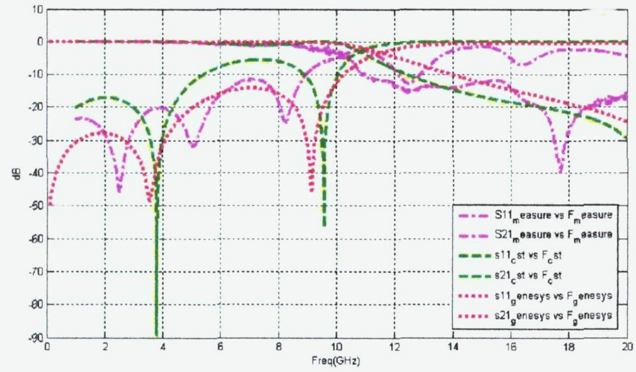


Fig.12 Output response obtained from Genesys, CST and VNA measurement.

VII. DISCUSSION

a. Low-k material

Fig. 12 and Table 3 shows the output response after adding the feeder line 50Ω. Compare to low pass filter without feeder line, this output response is improved. S11 and S21 for the cut off tightly same in Genesys and CST however after measured in VNA the output response has ripple and spike in S11 and S21. Its because of calebration to using VNA before measured the design and also because of solder that we are using to connect between SMA connector and microstrip.

b. High K material

Based on simulation, the low-pass filter implemented on the high-k material. The output response of low-pass filter keep unmoving, however the dimension reduce by 90% , center frequency and cut-off(dB) are reduced.

VIII. CONCLUSION

As the conclusion, this paper present Butterworth low-pass filter with third number of elements with feeder 50Ω and implement on the Rogers Duroid as a low-k material be able to contribute the good response and also output response in S11 and S21 from VNA.Then, by implement the low-pass filter on high-k material, the physical shape is reduced by 90% and the output response for S11 and S21 is still give low-pass nevertheless the output response has ripple and spike for S11 and S21.

IX. FUTURE DEVELOPMENT

The Butterworth low-pass filter could be further miniaturized by using gold as the conductor strip. The used of high-k substrate will result in miniaturization of the filter and could be used at higher frequency band.

ACKNOWLEDGEMENT

I would like to express my deepest gratitude and appreciation to my supervisor and co-supervisor, Pn. Kamariah Ismail and Pn. Suhana Sulaiman for their guidance, advices, supervision, and encouragement to me in finish this project. I also would like to say thanks to my lecturers and technician, Prof. Dr. Zaiki Awang, Pn. Ruby and En.Hisyam for helping and providing the substrate and SMA connector for this project. Finally I would love to say thanks to my family and all my friends for giving me encouragement to complete this project.

REFERENCES

[1] Prof. Zaiki Awang, *Microwave Systems Design Monograph,* 2008.
[2] Stan Gibilisco, "Handbook of Radio and Wireless Technology", 1998
[3] Inder Bahl, "Lumped Elements For RF and Microwave Circuits," 2003, p 353-354.
[4] Z.Awang, Microwave Sub-system Design, Tutorial Notes, Int. Wireless Tel Symp. 1999 (IWTS '99), Shah Alam, 1999
[5] M. H. Jarvis Drive, "Model 372XXA Vector Network Analyzer, Maintenance Manual," July 1996.
[6] Ian C Hunter, Stephen R.Chandler, David Young and Andrew Kennerly, "Miniatue Microwave Filters for Communication Systems", July 1995.
[7] G. Matthaei, L. Young, and E. M. T Jones, "Microwave Filrers, Impedance Matching Networks, and Coupling Structures." Nonvood, MA.: Artech House, pp. 172