Butterworth Band-pass Filter Using Parallel Coupled Lines

Mohd Ariff Bin Arifen
Faculty of Electrical Engineering,
Universiti Teknologi Mara,
40450 Shah Alam, Malaysia
Email: mohdariffarifen@gmail.com

Abstract - **This paper presents the design, simulation and analysis of a Butterworth Band-pass filter using parallel coupled line for microwave application. Butterworth approach was used in designing the filter and the simulation was carried out using two commercial simulation software. The performance of the filter was simulated based on low and high material (k) with different dielectric substrate (ε_r). The operating frequency range is 4 - 6 GHz with cut-off frequency of 5 GHz with the consideration of 40 % fractional bandwidth. It was observed that both the simulated and measured values were very close except for the insertion loss.**

Keywords: Filter, microstrip, parallel coupled line, low-k substrate, high-k substrate

I. INTRODUCTION

MICROSTRIP played an important role in much radio frequency (RF) or microwave applications. Emerging application such as wireless communication continue to challenge RF/microwave filter to operate in higher performance requirements, smaller size, lighter weight and lower cost [1]. Band-pass filter has the property that one band of frequency (the pass-band) is transmitted, while two band of frequencies, namely, those below and above the pass-band, are blocked (the stop-band).

Microwave filter [2]-[3] is a two port network used to control frequency response within a system by allowing the transmission of certain frequencies in the pass-band while attenuating frequencies in the stop-band. The parameters of the Butterworth filter consists of the length, *l* and the width of the coupled lines, *w* as well as the distance between the two coupled lines known as space gap, *s* [4].

Two microstrip lines were used as the main building block of parallel coupled line construction as shown in Fig. 1. In transmission line representation, both lines arrangement consist of input and output port where it is in open circuit condition as shown in Fig. 2.

This work consists of two parts. The first part of the work involved the design, simulation, fabrication and analysis of the filter based low-k substrate. The second part of the work focused on the design and simulation of the filter based on high-k substrate.

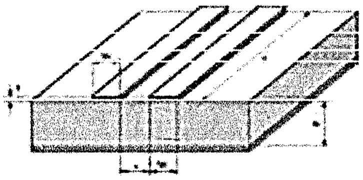

Fig. 1: Parallel coupled microstrip line

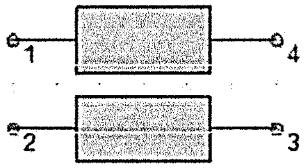

Fig. 2: Transmission line represented

II. SCOPE OF WORKS

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

Table 1
Band-pass Filter Design Specification

Number of order (n)	3
Center frequency	5 GHz
Lower cut-off frequency	4 GHz
Upper cut-off frequency	6 GHz
Bandwidth	2 GHz

Simulation on the effect of high and low-k substrate was also carried out to determine the effect of the physical shape and performance of the filter.

Finally, to produce a prototype Butterworth band-pass filter on Roger Duriod substrate with dielectric 2.33 for original dimension.

III. METHODOLOGY

Fig, 3 described all the work involved in designing the filter. Literature review was done to obtain information of Butterworth low-pass filter in low-k material. CAD tools was for designing and simulation purpose for both and high and low-k substrate.

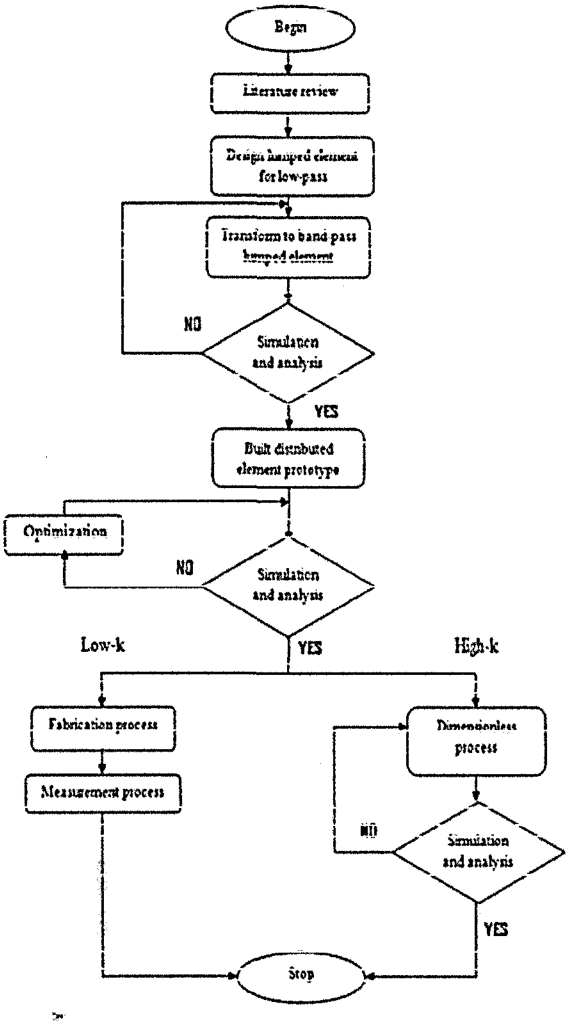

Fig. 3: Design flowchart

A. *Design procedure for low-k substrate*

Parallel coupled lines filter in this part was develop on Roger Duroid substrate where the characteristics as shown in Table 2.

Table 2
Roger Substrate Properties

Microstrip substrate

Dielectric constant	2.33
Height	0.508 mm
Loss tangent	0.0001
Roughness	0.0000 mm
Frequency	5 GHz

Microstrip conductor

Thickness	0.035 mm
Resistivity	1.000 rel Au

The first step to design a filter is to determine the filter specification such as operating frequency range, the order of the filter (N), and impedance matching of the filter. The filter is designed with N=3, which represent number of element of the filter. By referring to the design data of Butterworth low-pass filter, the element values obtained are g0 = 1, g1=1.00, g2=2.00., g3=1.00, g4=1.00. The quantities g is referred to the prototype elements value which is selected according to the order (n) of the filter from the Butterworth Table in [5]. The low-pass prototype elements values obtained can be represented as shown in Fig. 4. Based on the prototype values, the values are denormalized to obtain the actual value by using the following formula (1), (2) and (3).

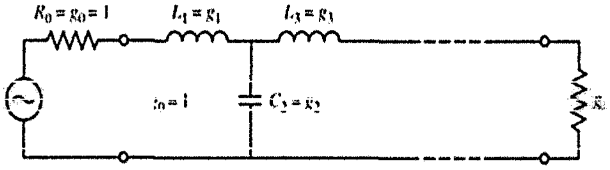

Fig. 4: Ladder circuit for low-pass filter prototype beginning with series element

$$L_n = R_g \times g(n) \quad (1)$$

$$C_n = \frac{g(n)}{R_g} \quad (2)$$

$$R_g = 50\ \Omega \quad (3)$$

For basic conventional band-pass filter design, the low-pass prototype was converted to band-pass prototype by computed the following calculation (5) to (14). The band-pass prototype elements values obtained can be represented as shown in Fig. 5.

Fractional bandwidth, $f_b = [\, f_b(\%) \times (f_c)] / 2$ (4)

Lower frequency, $f_l = f_c - f_b$ (5)

Lower ratio, $R_l = {f_l}/{f_c}$ (6)

Angular lower frequency, $\omega_l = R_l \times 2\pi \times f_c$ (7)

Upper frequency, $f_u = f_c + f_b$ (8)

Upper ratio, $R_u = {f_L}/{f_c}$ (9)

Angular upper frequency, $\omega_u = R_u \times 2\pi \times f_c$ (10)

Capacitors and inductors value:

$$L_1 = L_3 = \frac{L_n}{\omega_u - \omega_l} \quad (11)$$

$$C_1 = C_3 = \frac{\omega_u - \omega_l}{\omega_0^2 L_n} \quad (12)$$

$$L_2 = \frac{\omega_u - \omega_l}{\omega_0^2 C_n} \quad (13)$$

$$C_2 = \frac{C_n}{\omega_u - \omega_l} \quad (14)$$

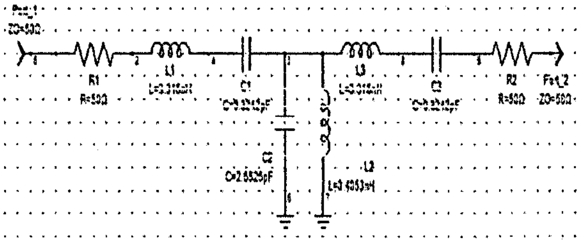

Fig. 5: Third order band-pass filter

All of the lumped elements components will undergo the translation process to the distributed elements due to the high operating frequency. Translation process has been done based on the value of the lumped elements to ensure that the distributed element for parallel blocked had a characteristics impedance value based on the lumped element prototype. To design such as structure that meets a particular band-pass filter specification; a number of computations have to be performed. The fractional bandwidth of the pass-band can be obtained by using the following equation in (15) The purpose of the fractional bandwidth calculation is to allow us to compute parameters such as first coupling structure, intermediate coupling structure and the final coupling structure which is referring to equation (16) till (18) respectively.

Fractional bandwidth

$$\Delta = \frac{\omega_u - \omega_l}{\omega_0} \quad (15)$$

First coupling structure:

$$Z_o J_{0,1} = \sqrt{\frac{\pi\Delta}{g_0 g_1}} \quad (16)$$

Intermediate coupling structure:

$$Z_o J_{i,j+1} = \frac{\pi\Delta}{2\sqrt{g_i g_{i+1}}} \quad (17)$$

Final coupling structure:

$$Z_o J_{n,n+1} = \sqrt{\frac{\pi\Delta}{2 g_n g_n + 1}} \quad (18)$$

The coupled line in Fig. 1-1 can be decomposed into even-mode excitation and odd-excitation [4]. To obtain the even and odd coupled line impedance Zo_e and Zo_o are calculated by using this equation (19) and (20) where $a = J_{i,i+1}$ and $Z_o = 50\Omega$. 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 (21).

$$(Z_{oe})_{i,i+1} = Z_o(1 + aZ_o + a^2 Z_o^2);\ \textit{even mode} \quad (19)$$

$$(Z_{oo})_{i,i+1} = Z_o(1 - aZ_o + a^2 Z_o^2);\ \textit{odd mode} \quad (20)$$

$$(Z_o)_{i,i+1} = \sqrt{(Z_{oe})_{i,i+1} \times (Z_{oo})_{i,i+1}} \quad (21)$$

Finally, coupling for each couple line is computed by using this equation (22). When even-mode and odd-mode impedance characteristics are determined from the calculation above, the physical parameter for each parallel coupled line such as width, length and lined spacing can be obtained from *Linecalc*.

$$C_{i,i+1} = 20 \log \left[\frac{(Z_{oe})_{i,i+1} + (Z_{oo})_{i,i+1}}{(Z_{oe})_{i,i+1} - (Z_{oo})_{i,i+1}}\right] \quad (22)$$

B. *CAD simulation for low-k substrate*

Simulation has been done by using *Genesys* and CST *Microwave Studio*. Distributed element prototype is depicted in Fig. 6. The 3D layout of the parallel coupled is illustrated in Fig. 7 based on the distributed element dimension. The final result for low-k substrate will briefly describe in next section.

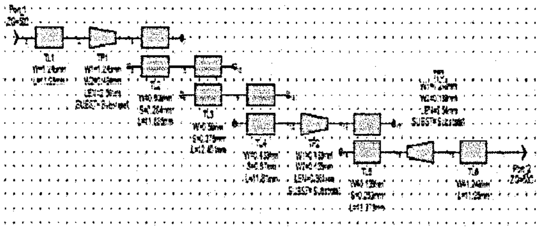

Fig. 6: Distributed element prototype

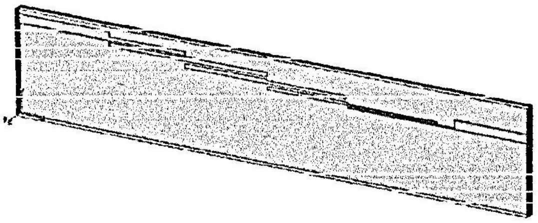

Fig. 7: Butterworth parallel coupled line band-pass filter physical layout

C. Design Procedure for high-k Substrate

High-k substrate is referred to higher dielectric constant. Similar simulation has been done based on band-pass parallel coupled as to low-k material. In [6], high–k substrate is used to miniaturize the overall dimension of the designed. The percentage reductions shown in Table 3 were applied on the filter dimension caused by specific parameters such as dielectric and thickness of strip conductor is varied.

Table 3
Transmission Line Reduction

Transmission Line (T.L.)	Original size (mm)		90 % reduction (mm)	
	Length (l)	Gap (s)	Length (l)	Gap (s)
T.L. 1	11.25	-	1.125	-
T.L. 2	11.686	0.284	1.1686	0.0284
T.L. 3	12.401	0.375	1.2401	0.0375
T.L. 4	11.81	0.37	1.181	0.037
T.L. 5	13.373	0.253	1.3373	0.0253
T.L. 6	11.25	-	1.125	-

D. CAD simulation for high-k substrate

Fig. 8 illustrates the CST simulation of parallel coupled filter employing high-k substrate. Simulation based on high-k substrate is performed to examine the effect of the filter. Fig. 9 shows the output response of the high-k substrate. Simulated result shows the frequency elements are shifted to the right at the certain operating frequency. The value of the insertion loss has approached to 0 dB while the return loss shifted downward until 50 dB. Although the values for all the parameters are different, the response still shown the behaviour of band-pass filter.

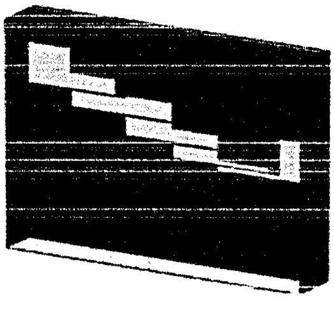

Fig. 8: Simulated layout prototype for high-k substrate

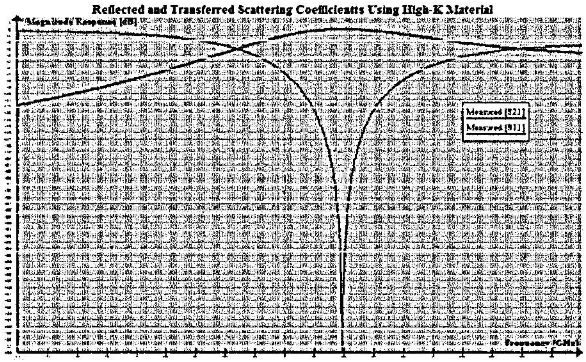

Fig. 9: Measured reflected (*S11*) and transferring (*S22*) coefficients

IV. RESULT AND DISCUSSION

Fabrication of the prototype was realized using the low-k material as shown in Fig. 10. Optimization procedure was used to obtain the best layout of the filter.

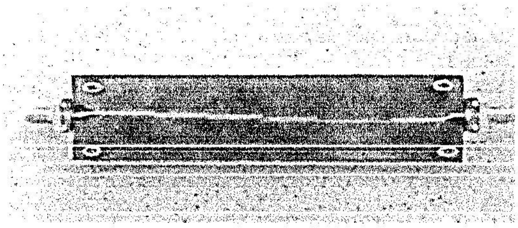

Fig. 10: Fabricated band-pass filter

Measurement of the parameters of the prototype was carried out using a vector network analyzer (VNA). Standard calibration [6] procedure was used prior to the measurement. Fig. 11 revealed a comparison between expected, simulated and measured results. There was a slight discrepancy between the three values for all the parameters. The discrepancy may be due to the parasitic losses. Other factors that caused the error were due to the effects of connectors and losses that arise from fabrication [7]. Table 4 shows the comparison between fabrication and simulation process.

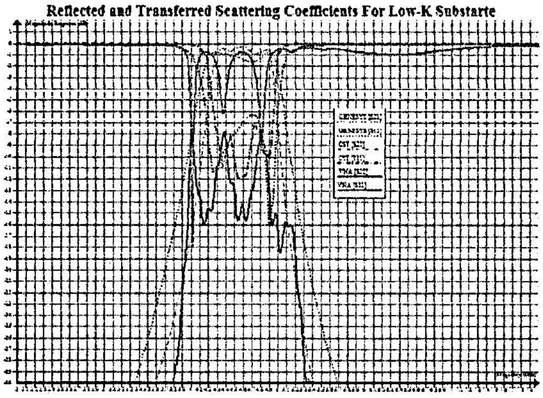

Fig. 11: Measured reflected (S11) and transferring (S22) coefficients

Table 4
Comparison of expected result, simulation result and measurement result

	Design specification	Simulated result using *Genesys*	Simulated result using *CST Microwave Studio*	Measured result
Center frequency (f_c)	5 GHz	4.67 GHz	4.59 GHz	4.4 GHz
Lower cut-off frequency (f_L)	4 GHz	4.16 GHz	4.215 GHz	3.994 GHz
Upper cut-off frequency (f_U)	6 GHz	5.18 GHz	4.965 GHz	4.806 GHz
Insertion loss (*S21*)	<-0.5 dB	-0.15 dB	-0.25 dB	-9.466 dB
Return loss (*S11*)	>-15 dB	-16dB	-12 dB	-18.095 dB
Bandwidth	2 GHz	1.02 GHz	0.75 GHz	0.812 GHz

V. CONCLUSION

This paper has presented the design and development of third order parallel coupled microstrip line band-pass filter using standard design equation on low and high-k substrates. Narrow bandwidth response has been achieved for the filter application on both substrates. Both substrate produce similarities in the shape response. The use of high-k substrate resulted in the shift of the operating frequency as well as ideal filter design specification was achieved.

VI. FUTURE DEVELOPMENT

The parallel coupled lines band-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.

ACKNOWLEDGMENT

The author would like to thank Suhana Sulaiman and Kamariah Ismail and all her team of researcher from the Microwave Technology Center at Universiti Teknologi MARA for their cooperation.

REFERENCES

[1] Teh Ghee Tean and Prof. Madya Hj. Ayob B. Johari, Design of Microstrip Bandpass Coupled Lines Filter, Kolej Universiti Teknologi Tun Hussein Onn (KUiTTHO).

[2] Gaobiao Xiao; Yashiro, K.; Ning Guan; Ohkawa, S. "An effective method for designing nonuniformly coupled transmission-line filter " *IEEE Trans. Microwave Theory Tech*, vol. 49, pp. 1027-1031, June 2001.

[3] M. L. Roy, et. Al., "The continuously varying transmission-line technique-application to filter design," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1680-1687, Sept. 1999.

[4] Selinda Lim, Huey Pin, "Hairpin Bandpass Filter Design," School of Electrical Engineering and Computer Science, University of Newcastle, Callaghan, NSW 2308, Australia

[5] Hong, J.S. and Lancaster, M.J., *Microstrip Filters for RF/Microwave Applications*, A Wiley-Interscience publication, Canada, 2001.

[6] M. H. Jarvis Drive, "Model 372XXA Vector Network Analyzer, Maintenance Manual," July 1996.

[7] Leo G. Maloratsky, "Review Basics of Microstrip Lines", *Rockwell Collins, 2100 West Hibiscus Blvd, Melbourne*, p.p. 79-88, March 2000.