

**DEVELOPMENT OF GRAPHICAL USER INTERFACE FOR
MICROWAVE FILTER DESIGN**

by

DJENGOMEMGOTO GERARD

Dissertation submitted to the Department of Electrical & Electronic
Engineering in partial fulfilment of the requirements
for the Bachelor of Engineering (Honours)
(Electrical & Electronic Engineering)

December 2013

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CERTIFICATION OF APPROVAL

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December 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

DJENGOMEMGOTO GERARD

ABSTRACT

Microwave filters play a sterling role in wireless communication systems and they are used to discriminate between wanted and unwanted signal frequencies. Designing microwave filter is a long process in going from the given specification through the synthesis and simulation to the final prototype. However, due to the unavailability of synthesized theoretical values of reactive elements in the market, the result may disagree with the expected output.

Moreover, the existing software tools cover only conventional filter topologies; modern microwave filter topologies such as Ultra Wideband (UWB) filter are not yet incorporated into these software tools. In addition, they are costly and not easy to use.

This research project aims at developing a low-cost, time-effective and a stand-alone graphical user interface (GUI) that will be used to design microwave filters. Throughout the projects, the main theory behind the technology of microwave filters, their generalized mathematical equations and the analysis of their different circuit topologies have been reviewed. This review helps to extract the necessary information needed for the design of microwave filters. Besides, the guiding principles and the underlying engineering factors for a successful and information-oriented GUI were also highlighted.

To carry out the project, the High-Level GUI Development Environment (GUIDE) together with a structured programming approach have been used to design the GUI, and to program its related functionalities. The frequency responses are generated by using the generalized equation of each filter class and type; and by using their different circuit topologies (Shunt or Series topology). The GUI can also provide reactive element values from given specification. Moreover, the features for the design of ultra wideband (UWB) band-pass filter, capacitively coupled and combine filter are also incorporated into the stand-alone application. The finalized prototype will serve both industries and educational institutions.

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LIST OF ABBREVIATIONS

FCC	: Federal Communications Commission
UWB	: Ultra Wideband
GUI	: Graphical User Interface
MatLab	: Matrix Laboratory
LPF	: Low Pass Filter
HPF	: High Pass Filter
BPF	: Band Pass Filter
BSF	: Band Stop Filter
RF	: Radio Frequency
Radar	: Radio detection and ranging
SoC	: System on Chip
EMI	: Electromagnetic interference
CAD	: Computer Aided Design
ADS	: Advanced Design Systems
HFSS	: Ansoft High Frequency Structure Simulator
GUIDE	: Graphical User Interface Development Environment
MCR	: MatLab Compiler Runtime
Z_o	: System impedance
UI	: User interface
LA	: Insertion Loss
LR	: Return Loss
N	: Order of the filter
L	: Inductor
C	: Capacitor
S	: Selectivity
ω_s	: Stopband frequency
ω_p	: Passband frequency
dB	: Decibel
Hz	: Hertz
GHz	: Gigahertz

CHAPTER 1

INTRODUCTION

This chapter focuses mainly on presenting a brief background on microwave filters and graphical user interface. It states also the problem and the objectives of this research project.

1.1 Background

For the last few decades, the world of high-speed computing devices and systems have seen tremendous improvements. The latter technological advancement results from the endless contributions and efforts of researchers, scientists, system designers or industries from various engineering disciplines. Meanwhile, the demand for higher bandwidth systems and high performing devices that can handle multi-gigabits data transmission over communication media is also scaling rapidly. Consequently, this demand for high frequency and high bandwidth systems becomes the defining backbone of the emerging technologies such as high-speed system design, system on chip (SoC), radio frequency (RF) and microwave system design, telecommunication, wireless communication, satellite communication, radio detection and ranging (RADAR)... In designing these complex communication systems, it is crucial to ensure that the final product complies with the normal and targeted communication standards. Besides, it should also have the ability to handle signal interferences, to suppress electromagnetic interference (EMI) or the jittery interferences that might occurs during the data transmission; the system should also have a proper defined frequency spectrum for a given transmission.

In the same perspective, microwave filters are used as two-port network to control the rejection of unwanted signal frequencies while allowing the desired signal frequencies to pass via a system [25]. These microwave filters are generally classified as Low-Pass (LP), High-Pass (HP), Band-Pass (BP) and Band-Stop. The

Band-Pass Filter can be broken down into narrow-band, wideband, ultra-wideband... Moreover, the latter type of BPF is still a novelty that has been seeing tremendous improvements.

Different techniques and methods have been used to design advanced microwave filters that help in maximizing the performance and effectiveness of high-speed devices used in modern communication technology [1]. In the same perspective, the Federal Communications Committee (FCC) released ultra-wideband (UWB) technology (with a bandwidth ranging from 3.1GHz to 10.6 GHz), a novelty in radio technology for the advancement in communication, networking, radar systems, imaging systems, and positioning systems, and gave the official authorization for the use of UWB technology and its commercialization in 2002 [2], [3]. Ever since, this new proposed technology has revolutionized the world of communication and networking industries and it has helped them to provide better services to their respective customers; UWB technology has become one of the major focus point and the center of research in microwave filters [4].

In line with this technological development, it is important to provide freshmen (in the area of microwave filter design), designers, innovators and researchers with new tools and platforms such as computer aided design (CAD) or graphical user interface (GUI) that will help in simplifying their work while boosting their efficiency but cutting down the design time. A GUI, with reference to [5], is defined as a pictorial interface to a program. The graphical user interface can help its user to better perform the data analysis and interpretation via the extraction of important design parameters and the display of data in both numerical value and graphical or pictorial form.

Throughout this research project, the emphasis will be put on the development of a graphical user interface (GUI) for the purpose of microwave filter design.

1.2 Problem statement

With the cutting-edge technology of RF and microwave devices used in high frequency applications, there are also powerful software and CAD tools available that help in the design of microwave filters or RF systems. In order to design RF systems or microwave filter for example, one or the combination of the following sophisticated platforms or simulation tools can be used for a computational design: Advance Design Systems(ADS) Agilent, Genesys RF and Microwave Design Software, Ansoft High Frequency Structure Simulator (HFSS), Microwave Office Design Suite, Cadence RF Design... However, designing microwave filters using these advanced tools requires a certain level of expertise, a strong programming skill or a very good knowledge in CAD.

It was reported that in order to master the functionalities and maximize the usage of ADS design tools, an intensive training and extensive exposure to the software's environment is required [14]. This makes it difficult to help beginners such as sophomores, freshmen or any starter to understand the fundamentals and basic theory behind microwave filter design before transitioning them to be familiar with high level microwave design and synthesis tools.

Similarly, due to time constraints in teaching microwave filters, as there are various materials to cover within a short period of time (approximately one semester), students are in need of software tools that will help them to easily practice computer simulations of microwave circuits for their homework and projects [30].

From professional designers' point of view, microwave filter design is a long and tiring journey towards reaching the final design and prototype. The process starts from the theoretical synthesis through schematic simulations to prototype fabrication and measurements. However, most of the time, the disagreement between the simulation and results occurs due to the unavailability of the synthesized theoretical values of the passive components in the market. Consequently, designers have to re-do the simulations due to undesired output.

Moreover, references [14] and [30] suggest that the existing software tools for microwave filter design are costly. In addition, modern filter topologies are not yet integrated in these filter design tools.

The proposed software tools in this project will incorporate both modern and conventional microwave filter topologies for industrial and educational applications. It will help users to get the 2D responses and their corresponding reactive element values from given specifications.

1.3 Objectives and Scope of Study

1.3.1 Objectives

The main objective of this research project is to develop a stand-alone graphical user interface (GUI) for microwave filter design. But most specifically, the intention is:

- ❖ To review the mathematical modeling of microwave filtering functions with their respective frequency responses.
- ❖ To design and build a graphical user interface that can stand-alone and help in the design of modern and conventional microwave filters.
- ❖ To provide a low-cost and time-effective software tool for industrial and educational applications.
- ❖ To generate responses using both 2D response emulation and simulation.

1.3.2 Scope of study

The scope of study covers basically all the necessary approaches and steps from the initial works to the final prototype resulting from this research project.

The primary works start with the identification of the design parameters and requirements. Throughout this phase, the main task is to find the input parameters and the basic valid design criteria for each type and class of microwave filter that will be incorporated into the GUI. This phase is followed by the initial drafts of the

GUI layout design and its implementation in Graphical User Interface Development Environment (GUIDE). After a successful design of the GUI, the next major task will be the programming of the user interface (UI) functionalities such as save button, plot button, reset button, exit button ...

The secondary works will focus on testing, debugging and running the finalized prototype of the GUI.

CHAPTER 2

LITTERATURE REVIEW

This chapter highlights briefly the technology and evolution of microwave systems, it covers also the key mathematical synthesis of microwave filtering functions, their respective transfer function using their scattering parameters (S-parameters), their ABCD matrix with relation to S-parameters through lumped elements and their design requirements. In addition, this section presents the previous works on GUI design and development for different applications and the fundamental design theory, principles or criteria behind GUI development using MATLAB software.

2.1 Theory of Microwave Filters

2.1.1 Basic Definition of terms relating to microwave filters

Before proceeding further, it is crucial to review the fundamentals resulting from the basic classification of microwave filters. In this generalized classification, each class of filter and its related concepts can be defined.

➤ Low Pass Filter (LPF): As the name of this filter class states "Low Pass", this filter passes only low frequency signals. That is to say, it allows signals with frequency from zero to cut-off frequency to pass and rejects all frequencies above its cut-off frequency.

➤ High Pass Filter (HPF): It blocks all signal frequencies lower than cut-off frequency while passing all signal frequencies higher than the cut-off frequency.

➤ Band Pass Filter (BPF): This filter passes only signal frequencies that are within its passband.

➤ Band Stop Filter (BSF): BSF rejects all frequency signals within the stopband and passes all signal frequencies that fall out of the stopband.

➤ Stopband refers to the frequency band that is occupied by the

unwanted signal frequencies.

➤ Passband refers to frequency band that is occupied by the desired signal frequencies.

➤ Transition band is the frequency band that allows the transition from passband to stopband or vice versa.

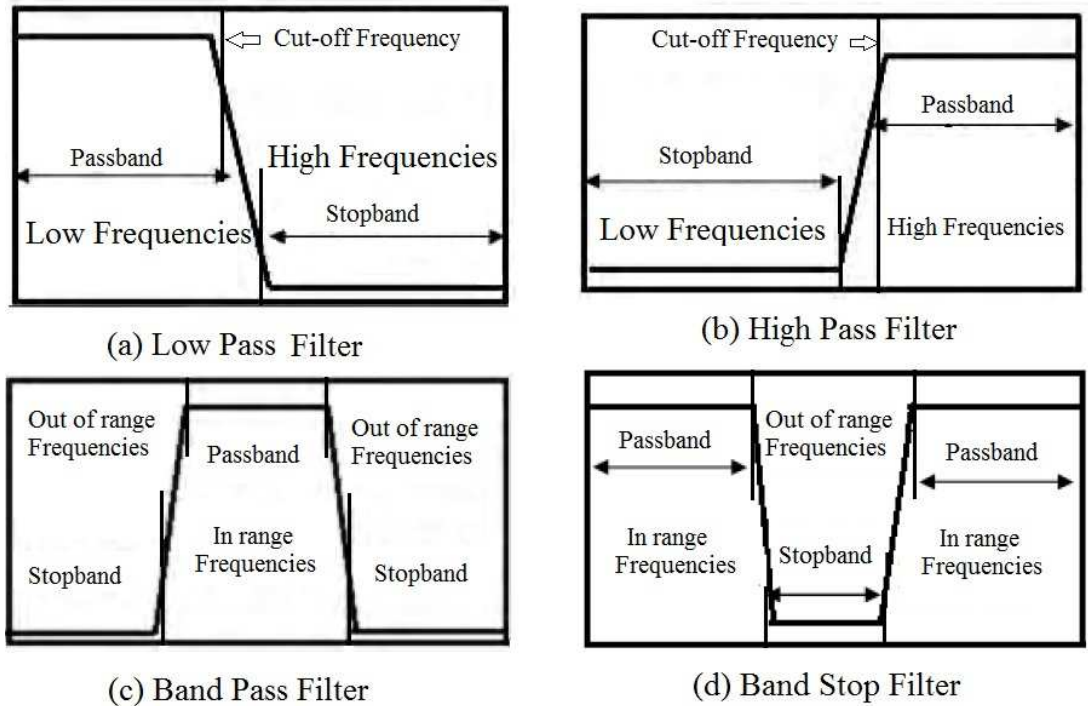


Figure 1 Frequency responses for the four classes of filters

2.1.2 Overview of Ultra Wideband (UWB) Filter

From the regulation issued by the FCC during the official release of UWB technology, three fundamental types of UWB systems have been defined [3]:

- Imaging systems.
- Communication and measurement systems.
- Vehicular and radar systems.

All UWB systems should be able to operate within the frequency band ranging from 3.1GHz to 10.6GHz. All signal being transmitted via UWB system should occupy a bandwidth (BW) of not less than 500MHz, the defined and selected signal BW is expected to be at least a quarter of the carrier or center frequency. With reference to this definition of UWB technology by the FCC, it is important to notice

that UWB systems and principally UWB filters are designed by incorporating both low pass filter (LPF) and high pass filter (HPF), the cascaded equivalence of LPF and HPF helps to create a dynamic UWB band-pass filter (BPF) [3], [13].

The technology of UWB systems have shown remarkable and excellent performance in its application for in wireless communication. It is able to transfer high data rate (100Mbps to 1Gbps) at the lowest power consumption compared to WiFi, IEEE 802.16, 2G or 3G but only for short distance (not more than 30 meters) applications. Figure (2) presents the difference between different wireless communication standards in of their respective data rates and supported ranges.

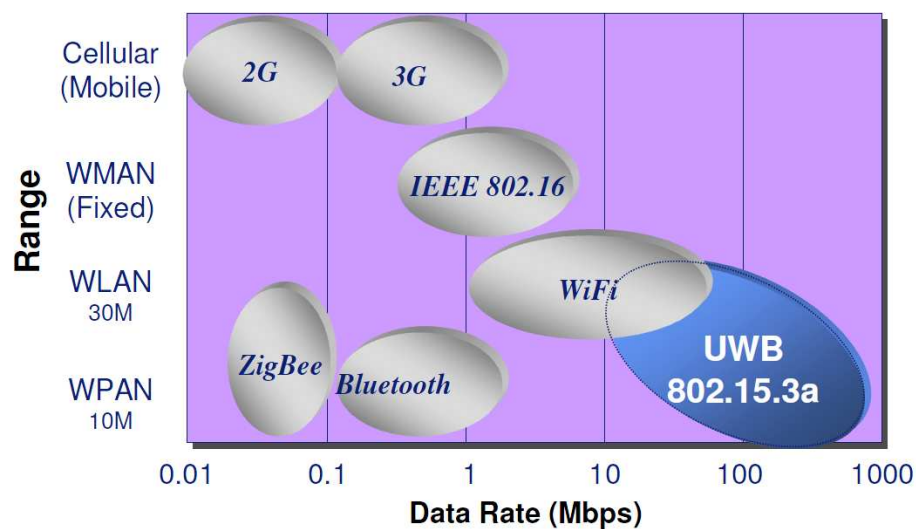


Figure 2 Data rate vs. Range for different wireless broadband standards [15].

2.2 Mathematical modeling of microwave filters

Microwave filters are mostly synthesized using different filter responses: maximally flat (Butterworth), equal ripple (Chebyshev), elliptic function, linear phase ... However, this project will mainly emphasize on Chebyshev and Butterworth filters as these two are the most commonly used attenuation characteristics in microwave filters [25].

2.2.1 Maximally Flat or Butterworth Filters

The generalized equation for Butterworth low pass prototype is specified by [25],[24]:

$$|S_{12}|^2 = \frac{1}{1 + \omega^{2N}} \quad (2.1)$$

Where $\omega \rightarrow \frac{\omega}{\omega_c}$, with ω_c as the cut-off frequency and ω as frequency variable.

N is the filter order, and it is related to the selectivity (S), the return loss (LR) and the insertion loss (LA) by:

$$N = \frac{L_A + L_R}{20 \log_{10}(S)} \quad (2.2)$$

$$\text{with } S = \frac{\omega_s}{\omega_p} > 1 \quad (2.3)$$

Where ω_s refers to the stopband frequency and ω_p the passband frequency. LR and LA are in dB.

The transfer function related to S_{11} can be expressed by using the following relationship:

$$|S_{12}|^2 + |S_{11}|^2 = 1 \quad (2.4)$$

2.2.1.1 Element values for Butterworth filter

The N (where N is the number of reactive elements) element values for a two-port network ended at both ends with a resistor using maximally flat filter characteristics can be computed as follow [25],[27]:

$$g_o = g_{N+1} = 1 \quad (2.5)$$

$$g_k = 2 \sin \left[\frac{(2k-1)\pi}{2N} \right]; \text{ where } k = 1, 2, 3, \dots, N \quad (2.6)$$

The related reactive elements for both series and shunt N-section LC ladder network are obtained through:

$$L_k = \frac{Z_o g_k}{\omega_c}; \text{ Series elements} \quad (2.7)$$

$$C_k = \frac{g_k}{Z_o \omega_c}; \text{ Shunt elements} \quad (2.8)$$

$$k = 1, 2, 3, \dots, N$$

The reactive elements (L and C) alternate depending on the ladder type (shunt or series) as shown in figure (3). Z_o is the system impedance.

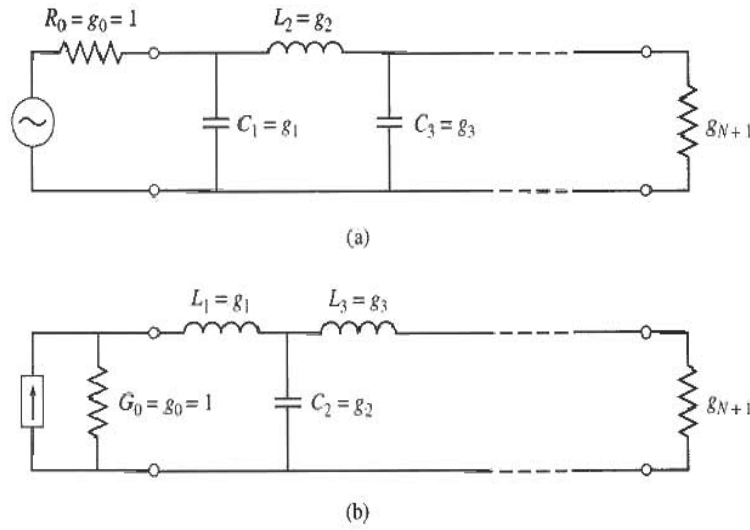


Figure 3 N-section LC ladder circuit with element definitions for LP prototype. (a) Prototype beginning with a shunt element. (b) Prototype beginning with a series element [27].

2.2.1.2 ABCD parameters and S-parameters

The ABCD parameters of a network is defined by the transfer matrix which is the result of a relationship between the input voltage and current to the output voltage and current [24].

$$T = \begin{vmatrix} A & B \\ C & D \end{vmatrix}$$

The transfer matrix for series impedance and shunt impedance network is defined in Figure (4).

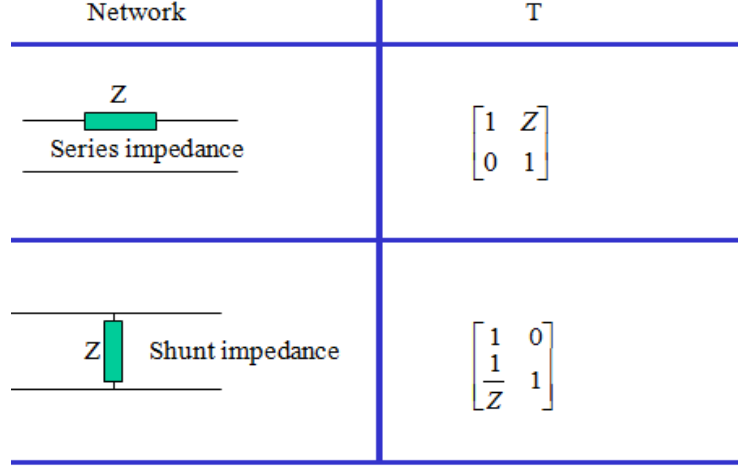


Figure 4 T matrix for shunt and series impedances [28]

For cascaded network like the N-section LC ladder network shown in figure (3), the total transfer matrix for both circuits can be obtained by matrix multiplication from the T matrix of the first reactive element till the T matrix of the last element.

By using the relationship that helps in converting the ABCD parameters to S-parameters [28], one can extract the expression of each S-parameter.

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \frac{1}{Z_o A + B + Z_o^2 C + Z_o D} \begin{bmatrix} Z_o A + B - Z_o^2 C - Z_o D & 2Z_o(AD - BC) \\ 2Z_o & -Z_o A + B - Z_o^2 C + Z_o D \end{bmatrix} \quad (2.9)$$

$$\Rightarrow S_{21} = \frac{2}{A + B/Z_o + Z_o C + D} \quad (2.10)$$

$$\Rightarrow |S_{21}|^2 = \frac{4}{|A + B/Z_o + Z_o C + D|^2} \quad (2.11)$$

Due to the symmetrical nature of maximally flat low pass prototype using its element values, deductively:

$$|S_{12}|^2 = |S_{21}|^2 = \frac{4}{|A + B/Z_o + Z_o C + D|^2} \quad (2.12)$$

Similarly, S_{11} and S_{22} can be expressed in term of ABCD parameters.

2.2.2 Equal Ripple or Chebyshev Filters

For Chebyshev response, the generalized filtering equation for low pass prototype is defined as [25]:

$$|S_{12}|^2 = \frac{1}{1 + \varepsilon^2 T_N(\omega)^2} \quad (2.13)$$

$$\text{Where } T_N(\omega) = \begin{cases} \cos(N \cos^{-1} \omega) , & |\omega| \leq 1 \\ \cosh(N \cosh^{-1} \omega) , & |\omega| \geq 1 \end{cases} \quad (2.14)$$

$$\omega \rightarrow \frac{\omega}{\omega_c} \quad (2.15)$$

$$\text{and } \varepsilon = \sqrt{10^{0.1L_{Ar}} - 1} \quad (2.16)$$

With ω_c referring to its cu-off frequency, ω the frequency variable and ε is the ripple level.

The filter order (N) of this filter response is related to its insertion loss (LA), return loss (LR) and selectivity (S) by:

$$N = \frac{L_A + L_R + 6}{20 \log_{10} (S + \sqrt{S^2 - 1})} \quad (2.17)$$

where S is defined by equation (2.3).

The passband ripple (L_{Ar}) can be computed by using the following mathematical expressions:

$$L_{Ar} = -10 \log_{10} (1 - \Gamma^2) \quad (2.18)$$

Where Γ refers to the reflection coefficient and it is related to the return loss (LR) by:

$$\Gamma = 10^{(-RL/20)} \quad (2.19)$$

2.2.2.1 Element values for Chebyshev filter

For low pass prototype using Chebyshev response, the reactive elements of the N-section LC ladder circuit portrayed in figure (3) can be obtained through these equations [25]:

$$\begin{aligned} \beta &= \ln \left[\coth \left(\frac{L_{Ar}}{17.37} \right) \right] \\ \gamma &= \sin \left(\frac{\beta}{2N} \right) \\ a_k &= \sin \left[\frac{(2k-1)\pi}{2k} \right] ; \quad k = 1, 2, 3, \dots, N \\ b_k &= \gamma^2 + \sin^2 \left(\frac{k\pi}{N} \right) ; \quad k = 1, 2, 3, \dots, N \end{aligned} \quad (2.20 - 2.23)$$

Therefore, the element values can be computed using:

$$\begin{aligned}
 g_o &= 1 \\
 g_1 &= \frac{2a_1}{\gamma} \\
 g_k &= \frac{4a_{k-1}a_k}{b_{k-1}g_{k-1}} ; k = 2,3,\dots,N \\
 g_{N+1} &= \begin{cases} 1 & \text{for } N \text{ Odd} \\ \coth^2\left(\frac{\beta}{4}\right) & \text{for } N \text{ Even} \end{cases}
 \end{aligned} \tag{2.24 - 2.27}$$

Where L_{Ar} is the passband ripple (dB).

The associated reactive elements are similar to those described by equations (2.7) and (2.8); and the resulting ABCD matrix and S-parameters can be computed using equations listed in section (2.2.1.2).

2.2.3 Low Pass to High Pass, Band Pass or Band Stop Transformation.

In microwave filter design, with the use of filter prototype transformation, it is possible to convert a low pass prototype to either high pass, band pass or band stop prototype. This transformation is done through a frequency substitution [24],[25].

➤ For low pass to high pass transformation, frequency substitution is done as follow:

$$\omega \longrightarrow -\frac{\omega_c}{\omega} \tag{2.28}$$

➤ When converting a low pass to band pass prototype, the low pass circuit undergoes the following frequency substitution:

$$\omega \longrightarrow \alpha \left(\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega} \right) \tag{2.29}$$

$$\text{where } \alpha = \frac{\omega_o}{\omega_2 - \omega_1} \text{ and } \omega_o = \sqrt{\omega_1 \omega_2} \tag{2.30 - 2.31}$$

With ω_o is the mid-band frequency and α is the bandwidth scaling factor.

➤ The last transformation is the conversion of a low pass prototype to band pass prototype which is achieved via this frequency substitution:

$$\omega \longrightarrow -\frac{1}{\alpha \left(\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega} \right)} \quad (2.31)$$

$$\text{where } \alpha = \frac{\omega_o}{\omega_2 - \omega_1} \text{ and } \omega_o = \sqrt{\omega_1 \omega_2} \quad (2.32 - 2.33)$$

With ω_o referring to the mid-band frequency and α the bandwidth scaling factor.

2.2.4 Extra classes of Chebyshev Band Pass Filter

2.2.4.1 Capacitively coupled Chebyshev Band Pass filter

The circuit topology for this filter class is shown figure (5).

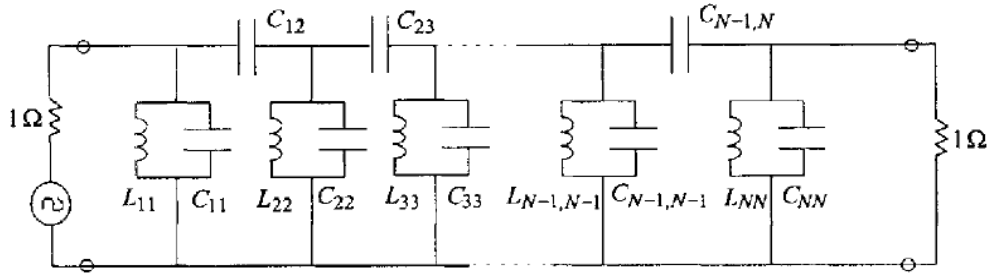


Figure 5 Circuit topology for capacitively coupled band pass filter [24].

With reference to [24], the reactive elements of this topology is derived using the following equations:

$$\eta = \sinh \left[\frac{1}{N} \sinh^{-1} \left(\frac{1}{\varepsilon} \right) \right]$$

$$C_r = \frac{2}{\eta} \sin \left[\frac{(2r-1)\pi}{2N} \right]; \quad r = 1, 2, 3, \dots, N \quad (2.34 - 2.36)$$

$$K_{r, r+1} = \frac{\sqrt{\eta^2 + \sin^2 \left(\frac{r\pi}{N} \right)}}{\eta}$$

Where the ripple level (ε) and the order of the filter (N) are described by equations (2.16) and (2.17) respectively.

By parameter values described in the above equations, the element values can be computed.

$$\begin{aligned}
C_{01} = C_{N,N+1} &= \frac{1}{\omega_o \sqrt{\alpha - 1}} \\
C_{r,r+1} &= \frac{K_{r,r+1}}{\alpha \omega_o} ; \quad r = 1, 2, 3, \dots, N-1 \\
C_{11} &= \frac{C_r}{\omega_o} - \frac{\sqrt{\alpha - 1}}{\alpha \omega_o} - C_{12} \\
C_{NN} &= \frac{C_N}{\omega_o} - \frac{\sqrt{\alpha - 1}}{\alpha \omega_o} - C_{N-1,N} \\
C_{rr} &= \frac{C_r}{\omega_o} - C_{r-1,r} - C_{r,r+1} ; \quad r = 2, 3, \dots, N-1 \\
L_{rr} &= \frac{1}{C_r \omega_o}
\end{aligned} \tag{2.37 - 2.42}$$

The filter order (N), the mid-band frequency (ω_o) and the bandwidth scaling factor (α) are computed using equations (2.17), (2.33) and (2.32) respectively.

2.2.4.2 Mathematical modeling of Chebyshev Ultra Wideband (UWB) BP Filter

Throughout the gradual evolution of UWB technology, different design techniques, models and structures for microwave filters have been used to build prototypes that comply fully with the standards of the UWB systems [16]. Among these structures that exhibit reliably the qualitative and quantitative behaviour of a successful ultra wideband system, the structure involving microstrip made up of a microstrip multi-mode resonator (MMR) and a parallel-coupled line at each end of the network. The basic configuration of this category of microstrip is portrayed in figure (6).

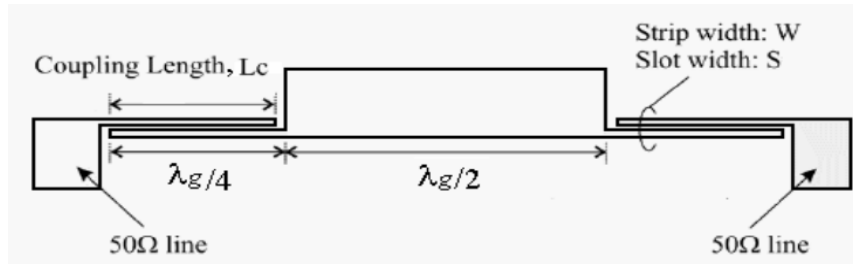


Figure 6 Basic schematic diagram of microstrip MMR with 2 parallel-couple lines at the two ends of the network [16].

Further improvements on the microstrip MMR based UWB systems in order to achieve better UWB passband behaviour have been done. Figure (7) depicts the layout of the MMR UWB band-pass filter (BPF) and its equivalent circuit diagram.

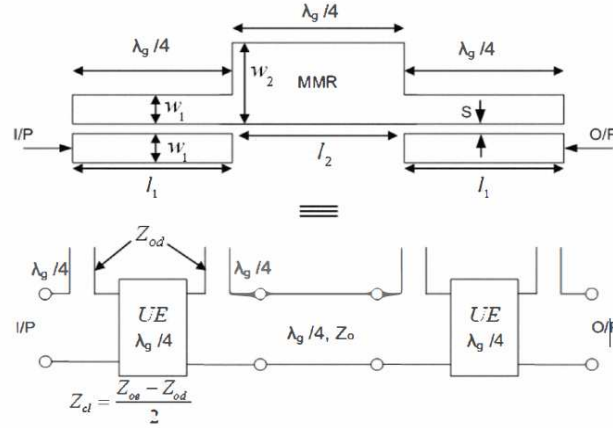


Figure 7 Layout and circuit diagram of MMR UWB band-pass filter [16].

Where l_1 refers to the coupling length, w_1 and w_2 the strip widths, s and λ_g refer to the slot width and the wavelength respectively. Z_o defines the characteristic impedance while Z_{oe} and Z_{od} are the related even-mode and odd-mode characteristic impedances of microstrip MMR based UWB BPF.

The mathematical modeling of UWB BPFs, that is presented in the following sections of this sub-chapter and adapted from reference [13], [17], was derived using the above described topology.

2.2.4.2.1 Fourth order UWB BPF

The filtering function, $T(\theta)$, for fourth order UWB band-pass filter is defined as the Chebyshev function by:

$$T(\theta) = \frac{A \cos^4(\theta) + B \cos^2(\theta) + C}{\sin(\theta)} \quad (2.43)$$

A reciprocal relationship can be established between the electrical length θ , the center frequency f_c (with $f_c = (f_{c(HPF)} + f_{c(LPF)})/2$) and the frequency f of the filter.

$$\theta = \frac{\pi}{2} \times \frac{f}{f_c} \quad (2.44)$$

Equation (1) presents the characteristic of a Chebyshev polynomial. For equal ripples in Chebyshev polynomial $T(\theta)$ with an inverse dependence in term of the filter frequency f , it is crucial to normalize $T(\theta)$. The restructured mathematical model of $T(\theta)$ is:

$$T(\theta) = \left(\frac{\varepsilon}{\bar{T}(\theta_{norm})} \right) \times \bar{T}(\theta) \quad (2.45)$$

Here, $\theta_{norm} = \frac{\pi}{2}$, $\bar{T}(\theta)$ and ε refers to the factor of the normalization of $T(\theta)$ and the ripple factor respectively. The ripple factor or ripple level (ε) is computed using equation (2.16).

$\bar{T}(\theta)$ is given by:

$$\bar{T}(\theta) = \frac{\cos^4(\theta) + \alpha \cos^2(\theta) + \zeta}{\sin(\theta)} \quad (2.46)$$

Where

$$A = \frac{\varepsilon}{\bar{T}(\theta_{norm})} \quad (2.47)$$

$$\alpha = \frac{B}{A} \quad (2.48)$$

$$\zeta = \frac{C}{A} \quad (2.49)$$

With $\theta_{norm} = \frac{\pi}{2}$, $\bar{T}(\theta_{norm}) = \zeta$, therefore the expression of A, B and C become:

$$A = \frac{\varepsilon}{\zeta}, \quad B = \frac{\alpha \cdot \varepsilon}{\zeta} \quad \text{and} \quad C = \varepsilon.$$

α and ζ components can be computed from their relationship with the bandwidth ($BW = f_{c(HPF)} - f_{c(LPF)}$) while complying with $\alpha^2 - 4\zeta > 0$ and $\alpha + \zeta + 1 > 0$ inequalities.

$$\alpha = \frac{3}{4} \left[\cos\left(\frac{BW}{2}\right) + \frac{1}{3} \right]^2 - \frac{4}{3} \quad (2.50)$$

$$\zeta = \frac{1}{4} \sin^2\left(\frac{BW}{2}\right) \left[1 - \cos\left(\frac{BW}{2}\right) \right] \quad (2.51)$$

Nota Bene: The bandwidth (BW) value in GHz should be converted to its equivalent value in radian using equation (2.44) prior to the computation of α and ζ expressed in equation (2.50) and (2.51).

The following table summarizes the values of ε for different return losses.

Table 1 Return Loss (LR) and its equivalent Ripple Factor or Ripple Level

Return Loss (RL) (dB)	Reflection coefficient	Passband Ripple (dB)	Ripple Factor
1	0.8913	6.8683	1.9652
2	0.7943	4.3292	1.3076
3	0.7079	3.0206	1.0024
4	0.6310	2.2048	0.8133
5	0.5623	1.6509	0.6801
6	0.5012	1.2563	0.5792
7	0.4467	0.9665	0.4993
8	0.3981	0.7494	0.4340
9	0.3548	0.5844	0.3795
10	0.3162	0.4576	0.3333
11	0.2818	0.3594	0.2937
12	0.2512	0.2830	0.2595
13	0.2239	0.2233	0.2297
14	0.1995	0.1764	0.2036
15	0.1778	0.1396	0.1807
16	0.1585	0.1105	0.1605
17	0.1413	0.0875	0.1427
18	0.1259	0.0694	0.1269
19	0.1122	0.0550	0.1129
20	0.1000	0.0436	0.1005

The transfer functions for UWB BPF are related to $T(\theta)$ by the following equations; their expressions in term of A and $\bar{T}(\theta)$ can also be derived using equation (2.45) and (2.47). Therefore:

$$|S_{11}(\theta)|^2 = \frac{T^2(\theta)}{1+T^2(\theta)} \Rightarrow |S_{11}(\theta)|^2 = \frac{\bar{T}^2(\theta)}{A^2 + \bar{T}^2(\theta)} \quad (2.52)$$

$$|S_{21}(\theta)|^2 = \frac{1}{1+T^2(\theta)} \Rightarrow |S_{21}(\theta)|^2 = \frac{1}{1+A^2 \cdot \bar{T}^2(\theta)} \quad (2.53)$$

From these equations, the dB expression of $|S_{11}(\theta)|^2$ and $|S_{21}(\theta)|^2$ for graphical analysis of their respective frequency response can be computed accordingly.

$$|S_{11}(\theta)|^2_{(dB)} = 20\log_{10} \bar{T}(\theta) - 10\log_{10} (A^2 + \bar{T}^2(\theta)) \quad (2.54)$$

$$|S_{21}(\theta)|^2_{(dB)} = -10\log_{10} (1 + A^2 \cdot \bar{T}^2(\theta)) \quad (2.55)$$

The graphical form of the $|S_{11}(\theta)|^2$ and $|S_{21}(\theta)|^2$ are portrayed in the following figure.

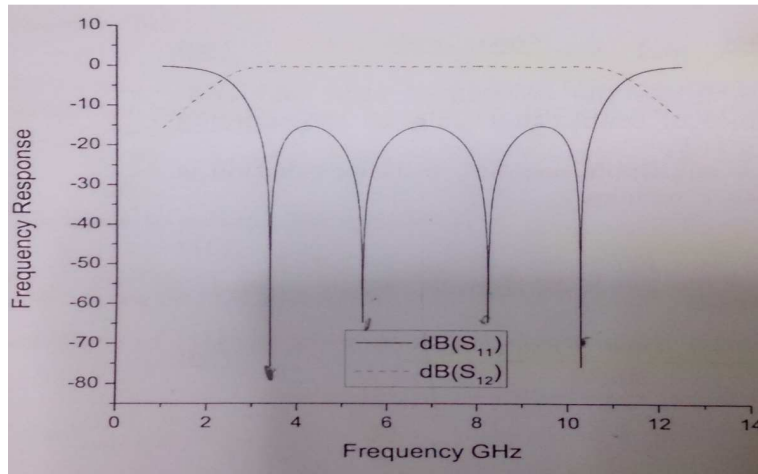


Figure 8 Frequency response of 4th order UWB BPF [17]

2.3 Graphical User Interface (GUI) Design

GUI plays an important role as the medium between the user and a computer program. The user interface provides the user with an environment integrated with interactive controls, commands, feedbacks ... with a predictive response. A simple example of human and computer interface is described in figure (9).

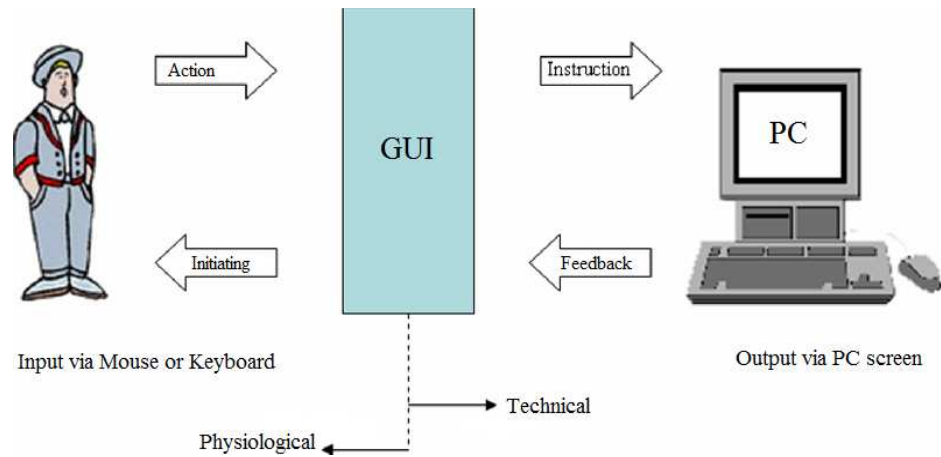


Figure 9 Human and GUI interaction [21].

2.3.1 Fundamental Principles for GUI design

According to a recent study conducted at the Xi'an University of science and technology, a number of design considerations and criteria such as dynamism, consistency and attractive visual appearance of the user interface, its layout and functions have been analyzed with respect to consumer's need, desire, taste and likes [20]. This important study was done using Kansei Engineering (KE), an engineering discipline with emphasis on implicit satisfaction and pleasure of consumer prior to product design, highlights the importance of the interaction between humans and the user interface and shows how the consideration of human's cognitive psychology and anthropology on the artificial intelligence of the GUI can help to boost the product's market.

According Martin [22], there are three fundamental design factors for a successful and information-oriented GUI: the development factors, the visibility factors and the acceptance factors. Similar to the study done by Sun [20], these three factors covers the basics requirements that are deemed fit in term of their compliance with human's anthropological and psychological perception. Moreover, Martin [22] has provided some guiding principles to be followed when designing a graphical user interface. For a successful GUI design, it is imperative to organize the layout design properly, to economize the window of the interface and to make a user friendly GUI. In figure (10) bellow are examples of a "good layout" and "bad layout" structures of a GUI.

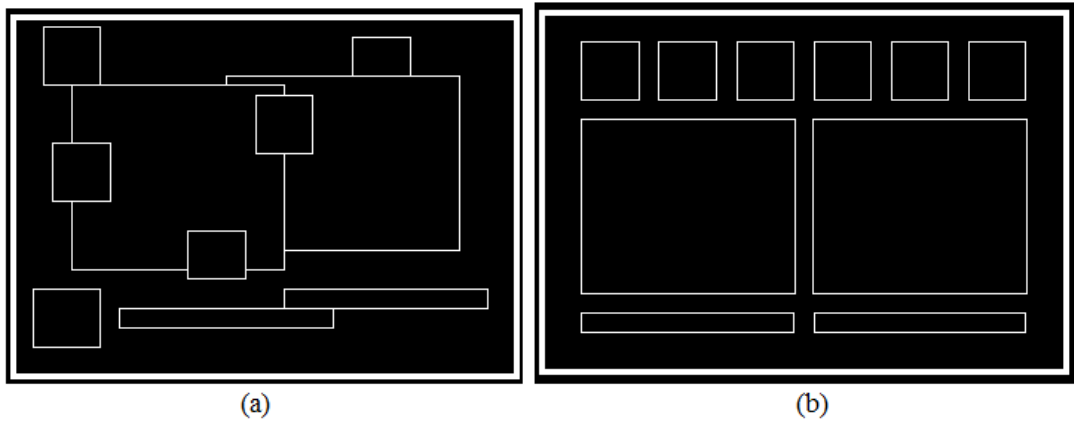


Figure 10 (a) Chaotic layout for GUI, (b) Ordered layout for GUI [22]

2.3.2 MATLAB GUI

MATLAB GUI, like other graphical user interfaces, is to help people without a good command of programming language to be able to interact with the machine without the need to master it [23]. Marchand and Holland [23] continue on suggesting and defining the design stages involved in the development of a GUI using MATLAB software. Prior to the GUI design, the developer should make a proper analysis by identifying the end user and defining the user guide. This stage should be followed by the layout design of the user interface based on the analysis done during the first design stage and KE design considerations. Then, the designer should draft and sketch skillfully its layout design on a piece of paper before proceeding to the actual design and construction of the GUI.

When designing GUI using MATLAB, Marchand and Holland [23] present two different approaches: GUI Development Environment (GUIDE) technique and Programmatic approach.

❖ In Low-Level MATLAB GUI programming approach, the developer program the GUI using M-File, all the graphic elements of the interface are also programmed along with the GUI. In this approach, the designer should define all the functions or Callbacks involved.

❖ In High-Level GUI Development Environment (GUIDE) approach, compared to the programmatic approach which involve a lot of "hand-programming" for the creation of the GUI, this new technique uses the embedded feature (GUIDE) of MATLAB to create the complete GUI which can be saved as FIG-file. However, once the GUI is designed, all the Callback functions need to be programmed accordingly. The complete GUI layout editor shown in figure (11) is obtained by entering the **guide** at the command prompt.

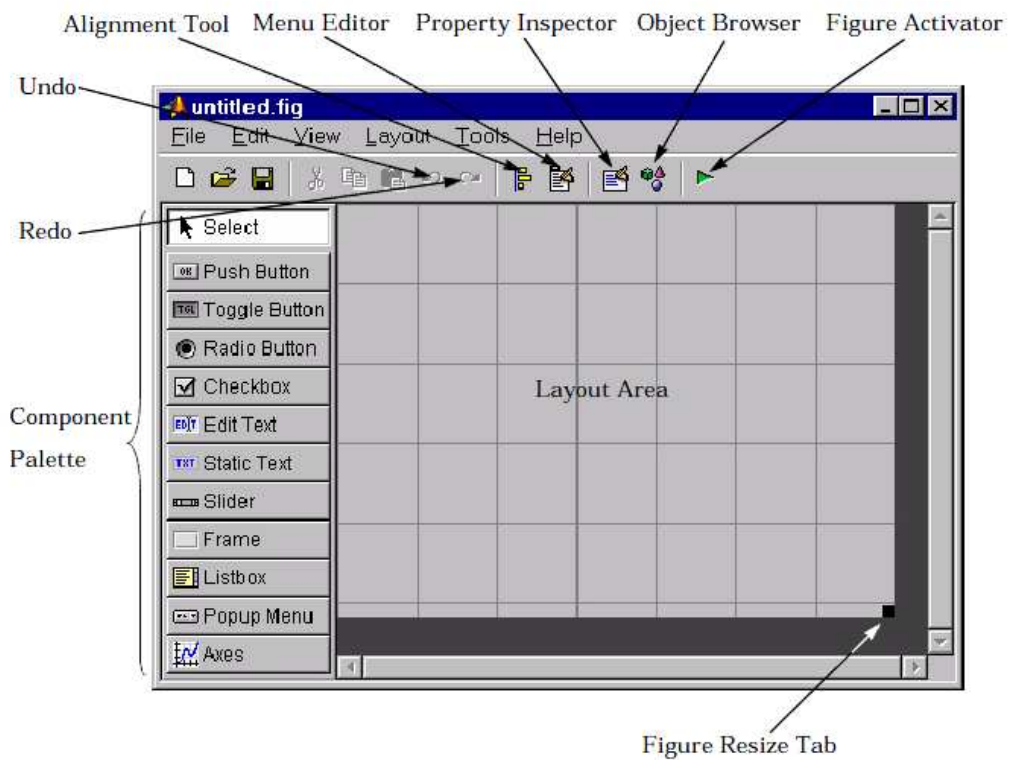


Figure 11 GUI Development Environment (GUIDE) Layout Editor [29].

CHAPTER 3

METHODOLOGY

This chapter focuses on the methodology that will be used in the conduct of this research project. It comprises of research methodology, project activities, key milestones, Gant Chart and tools used.

3.1 Research Methodology

Prior to stepping into the design phase of the user interface, a deeper exploration, research and review were conducted on the fundamental theories of microwave filters. The primary research was intended to help in grasping the behavior of each filter type and class; their respective frequency response characteristic and the identification of the major key elements needed for the design of a given class of filter. Moreover, some of the key factors, guiding principles and procedures for the design of a dynamic, user-friendly and marketable graphical user interface have been highlighted.

In order to carry out this project, which is to develop a stand-alone GUI for microwave filter design, the high-level GUI development environment (GUIDE) approach will be used to design the layout of the graphical user interface. The related M-file will then be used to program all the callback functions of the user interface. Moreover, all the filtering function, parameters, coefficients, frequency responses ... of the filter derived in **section 2.2** will be used to develop a proper algorithm to be integrated with the designed GUI. The finalized design will be tested for consistency, debugged for any designed error that might occur and submitted for educational and industrial use.

3.2 Project main activities and Gantt Chart

The brief and simplified Gantt Chart of the design methodology is presented figure (12).

<i>ID</i>	<i>Project Activities</i>	<i>Start</i>	<i>Finish</i>	<i>Duration</i>
1	Identifying the Design Requirements	20/5/2013	31/5/2013	2w
2	Identifying the Design Parameters	27/5/2013	7/6/2013	2w
3	Drafting the Layout Design of GUI	7/6/2013	20/6/2013	2w
4	Designing the GUI in MatLab GUIDE	21/6/2013	25/7/2013	5w
5	Programming the UI Controls	1/7/2013	25/11/2013	21.2w
6	Saving and Running the GUI	25/11/2013	29/11/2013	1w
7	Testing and Debugging the GUI	29/11/2013	2/12/2013	.4w
8	Finalizing the GUI Design	2/12/2013	10/12/2013	1.4w

Figure 12 Gantt Chart and main project activities

3.3 Microwave Filters Programming

The adopted algorithm, which is used to program the filtering functions, frequency responses and the related design parameters for microwave filter, is presented in the form of flow chart in figure (13,14). This flow chart shows also how the graphical user interface will operate. The user will need to select the desired type and class of microwave filter on the user interface. The GUI will take the valid input parameters (such as return loss, insertion loss, pass-band or stop-band frequencies, filter bandwidth ...) from the user. The next task of the GUI is to proceed to displaying the graphs and important data needed by the user on the user interface.

Generation frequency responses of of Chebyshev or Butterworth Filter

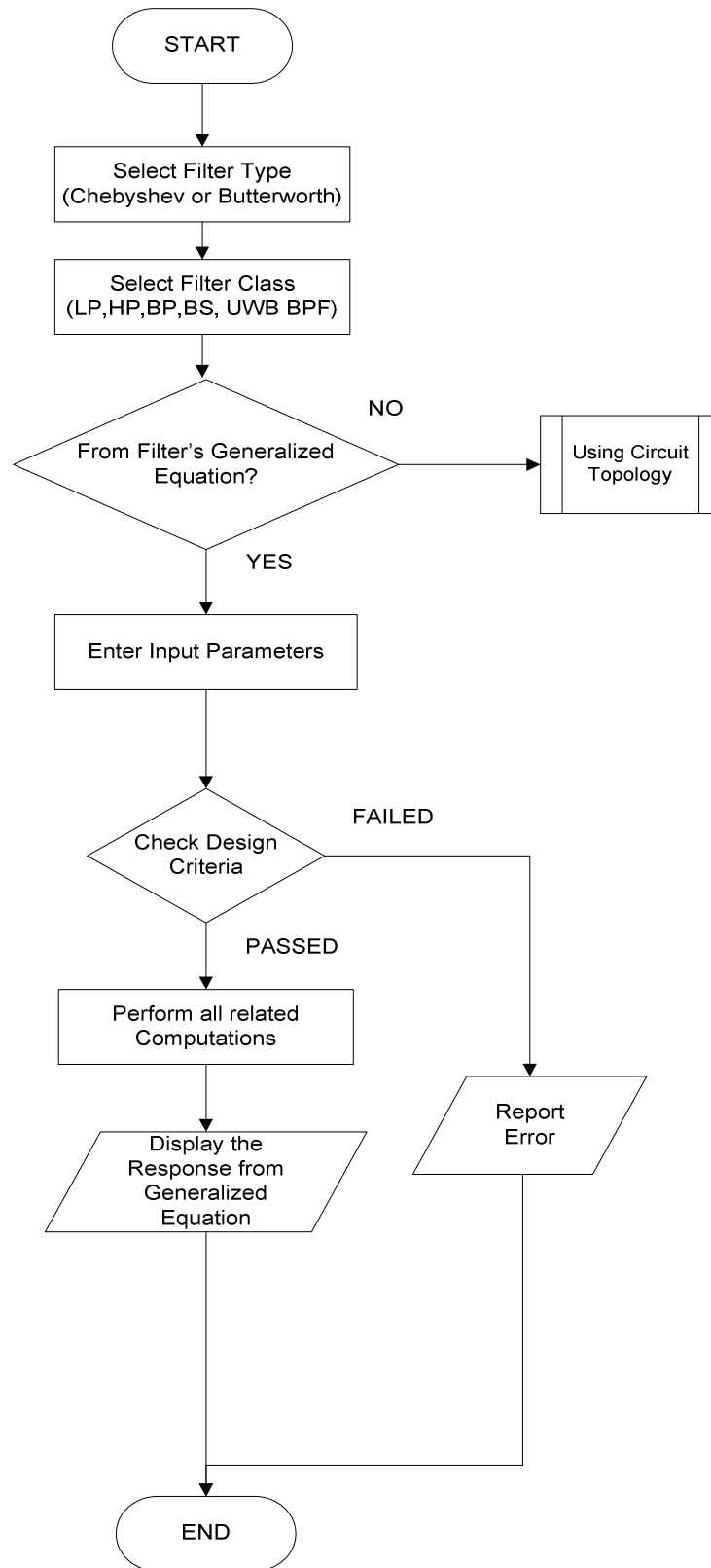


Figure 13 Flow Chart used in programming the generalized Chebyshev and Butterworth filter responses.

Frequency Response from Circuit Topology

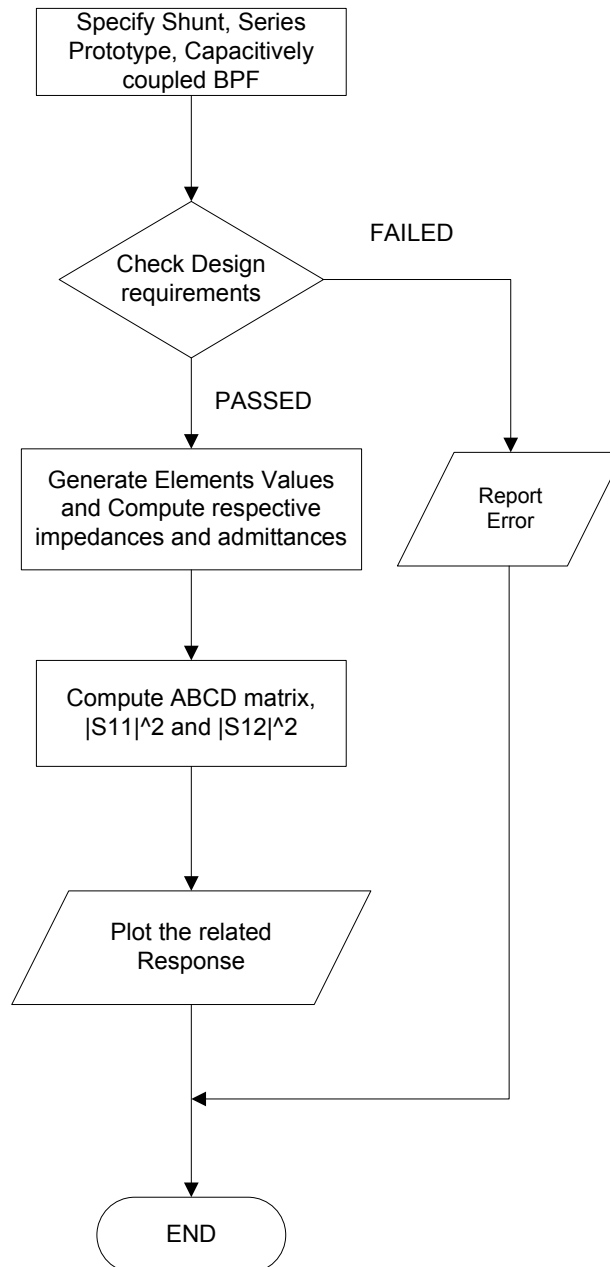


Figure 14 Flow Chart used in programming the Chebyshev and Butterworth filter responses from their respective circuit topologies.

3.4 Stand-alone GUI and MatLab Compiler Runtime (MCR)

The developed GUI (in MatLab) can be deployed and converted into an executable (.exe) file. The deployed MatLab GUI project can successfully run on

computers with no MatLab software installed, however the stand-alone GUI can run on those computers with the help of MCR. The MCR is a set of libraries that help to run MatLab applications or components on computers with no MatLab installed, it is free to use, to distribute and it can be downloaded via MathWorks website. This MatLab Compiler Runtime is available for Windows, Linux and Mac operating systems.

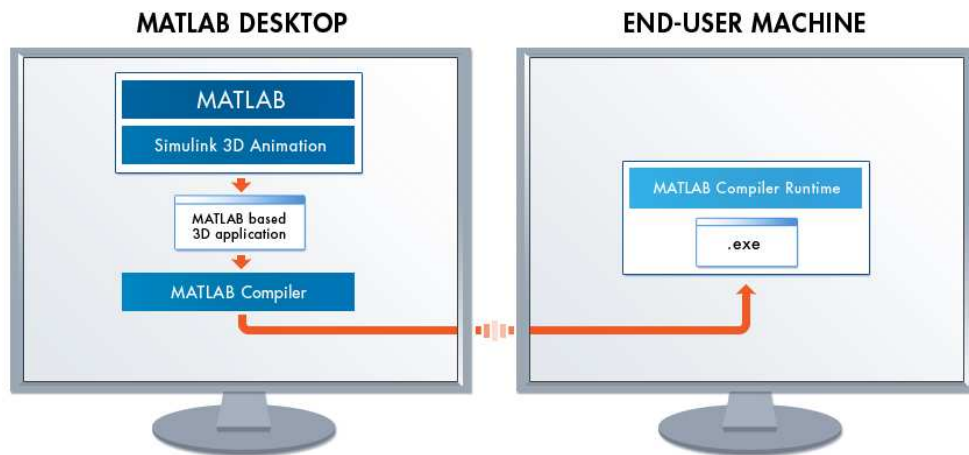


Figure 15 MCR and MatLab stand-alone applications

CHAPTER 4

RESULTS AND DISCUSSION

This chapter is objectively intended to provide the results of the research project. It presents a concise information on the GUI's artificial intelligence and user interface controls' operations. An ample discussion is also made on the subject matter.

4.1 Programming approach of the GUI and the Transfer Functions.

Structured programming approach was adopted for the design of the GUI, to write its related program codes for both transfer functions and user interface controls. Structured programming approach is the most commonly used approach in software development. By making use of the control structures (sequence, selection and repetition) that this approach provides, the application will be easier to debug, modify and its program code will be easier to understand.

4.1.1 Coding the Transfer Functions

The MatLab M-file has been used to program the transfer functions of all the classes of filters that are incorporated in the final prototype. The integrated microwave filters are listed as in table (2).

Table 2 Chebyshev and Butterworth Filters incorporated into the GUI.

Total number of responses	Filter Types	Filter Classes	Filter Responses generated using
15	Chebyshev	LPF HPF BPF BSF	<ul style="list-style-type: none"> ● Chebyshev Generalized Equations ● ABCD Matrix
12	Butterworth	LPF HPF BPF BSF	<ul style="list-style-type: none"> ● Butterworth Generalized Equations ● ABCD Matrix

In total, the GUI will enable its users to design microwave filters for four filter classes using both Chebyshev and Butterworth responses to generate up to twenty seven (27) responses using different techniques and approaches.

More importantly, the programmatic approach that has been adopted in handling each and every filter response differs with reference to each filter's prototype, topology, parameters, characteristics, definition and complexity. The following figure provides a fragment of the code used to generate Chebyshev low pass shunt prototype.

```

Tnew = T*[1 Z(t);0 1];
T = Tnew;
elseif k==1
    % Computing Z(C) values
    Z(t) = Z*Element(t).*w(i);
    % T matrix
    Tnew = T*[1 0;Z(t) 1];
    T = Tnew;
else
end
else
end
end
end
T;
% Getting ABCD values by identification using 2X2 Matrix T=[A B;C D] by using
A = T(1,1);
B = T(1,2);
C = T(2,1);
D = T(2,2);
% Computing S12 and S11 values for different values ABCD resulting from the
% variation in w.
Sa(i) = abs(2./(A+(B./Zo)+(C.*Zo)+D));
Sb(i) = abs(1 - abs(2./(A+(B./Zo)+(C.*Zo)+D)).^2);
end

```

Figure 16 Fragment code used to generate Frequency Response for Chebyshev Low Pass Shunt Prototype.

4.1.2 Design and implementation of the GUI in MatLab

The application has been designed in MatLab using its built-in tool (the Graphical User Interface Development Environment or GUIDE). The development of this GUI is characterized by the simplicity of the interface for the users to be easily familiar with it. It is intended to help users to perform a straight forward design by selecting the type and class of the filter, the next step will be just to key in the input parameters in order to obtain advanced graphical displays and numerical data for further analysis. The finalized user interface of the stand-alone application is portrayed in figure (17).

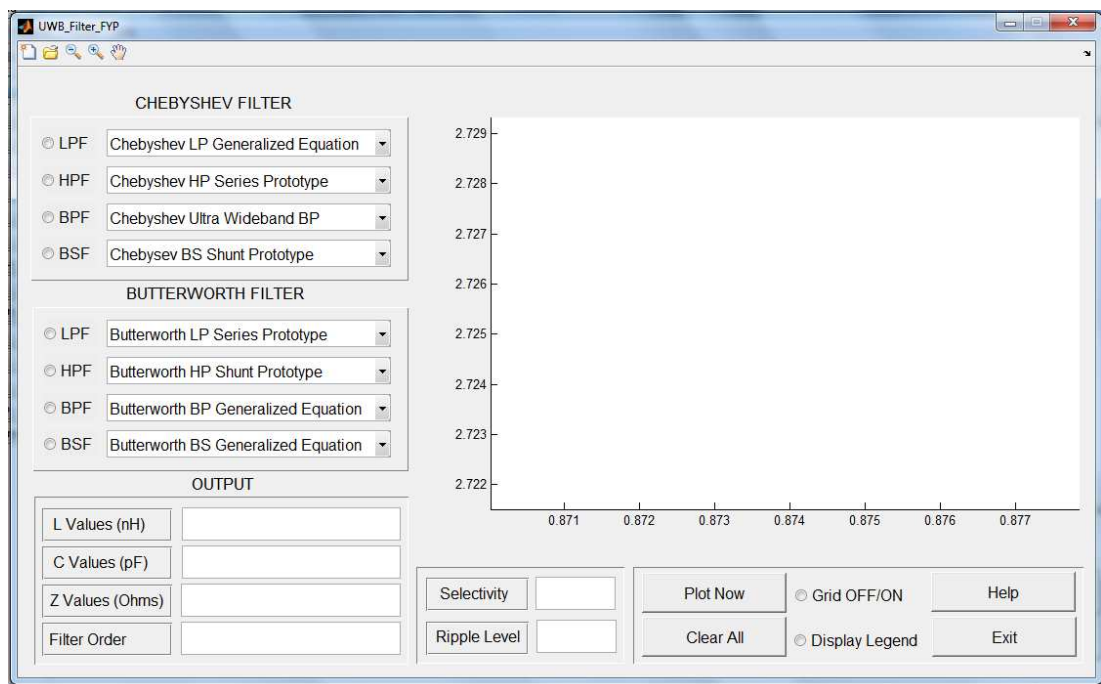


Figure 17 The user interface of the developed application for microwave filter design.

The related MatLab M-file has been used to write the program codes relating to the user interface controls (help dialog box, input dialog box, radio buttons for filter classes, exit button, save button...) of the GUI. The manipulation of this user interface controls helps in creating a dynamic artificial intelligence for this GUI that will make the user aware before making any unwanted, undesired or involuntary decision. The GUI can also inform the user through a pop-up dialog box in case the input parameters violate the design requirement.

In addition, the four classes of filters (LPF,HPF,BPF and BSF) for both Chebyshev and Butterworth filter type can be designed only one at a time. That is to

say, if a radio button of Chebyshev low pass is selected, all the remaining buttons will be automatically inactive.

The finalized prototype is deployed and converted into an executable (.exe) format. The converted format can run as a stand-alone application by using the set of libraries provided in MatLab Compiler Runtime (MCR).

4.1.2.1 *Demonstration of microwave filter design using the GUI*

4.1.2.1.1 *Chebyshev Low Pass Filter*

In order to proceed to the design of Chebyshev LP filter, the user has three options (Chebyshev LP Generalized Equation, Chebyshev LP Shunt Prototype and Chebyshev Series Prototype) through the pop-up menu next to LPF under Chebyshev filter. The final step to displaying the response of the desired filter is to hit the plot button, a pop-up of input dialog box will be automatically displayed for the user to key in his/her data followed by a single click on the "OK" button of the pop-up input dialog box.

A step by step illustration of the situation described above is shown in the following figures.

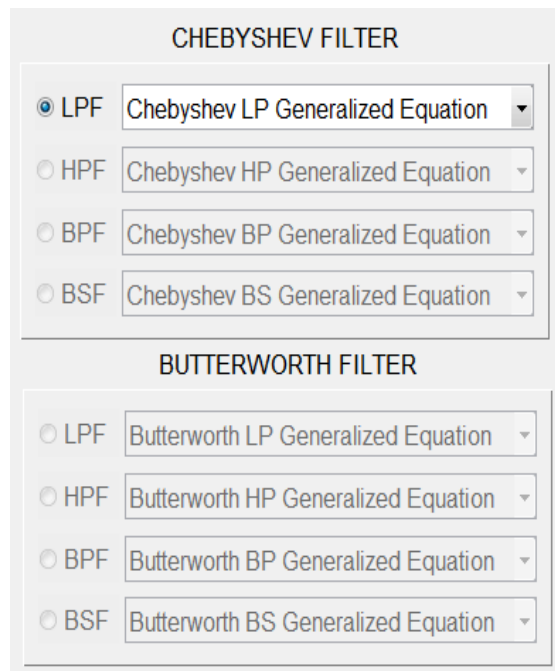


Figure 18 First Step: Select filter type and class

After hitting on the "Plot Now" button, this input dialog box will pop-up, the user will need to enter the input data in their respective field. The user will be

required also to hit the OK button in order to proceed to the display of the filter's frequency response.

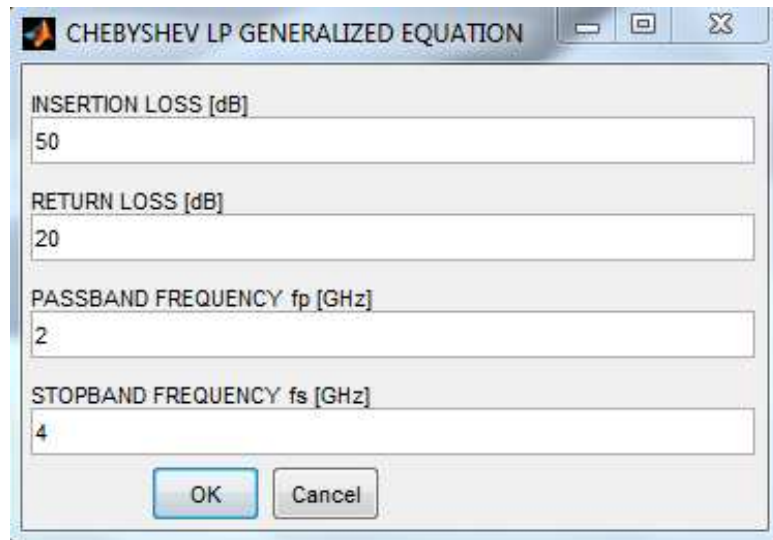


Figure 19 Second Step: Pop-up of the input dialog box, key in input data.

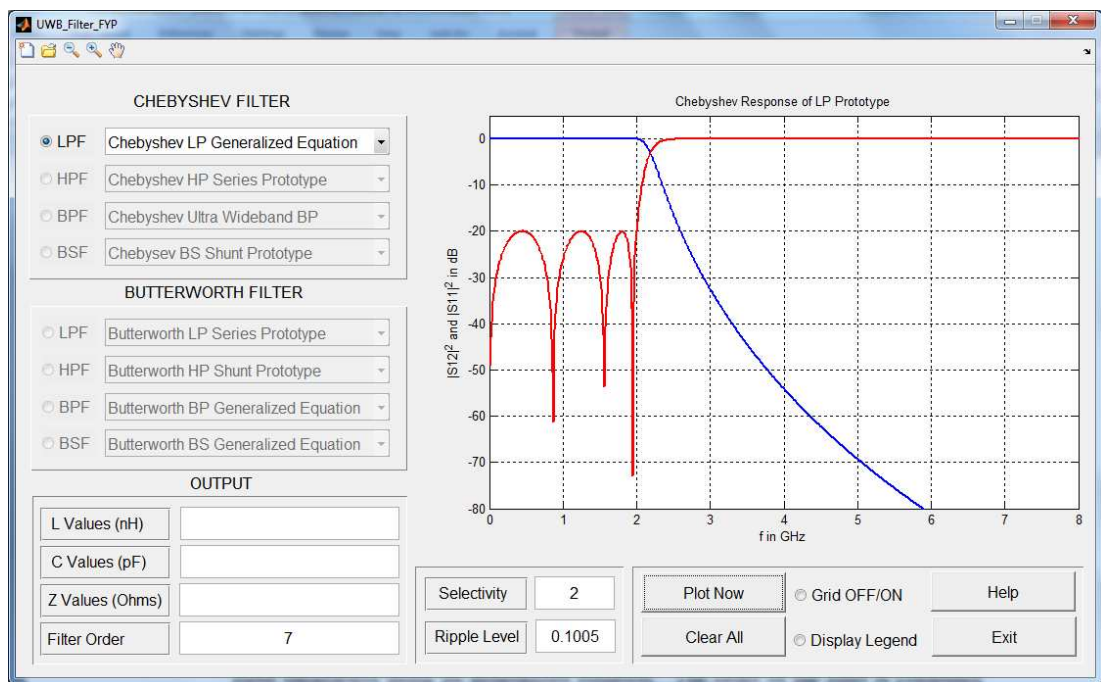


Figure 20 Final Step: Display of Frequency Response of the selected filter.

This Print Screen of the GUI shows the frequency response of the Chebyshev low pass filter with reference to the user's selection of filter type, filter class and input parameters using its generalized equation. The order of the filter is computed using the input data and displayed in the field of "Filter Order" at the left side of the

GUI; the selectivity and the ripple level are also displayed in their respective fields.

4.1.2.1.2 Chebyshev High Pass Filter

For the case of high-pass filter, responses can be generated. An example of 7th order Chebyshev HPF Series prototype is illustrated in the figures below. The first step is the same for all filter types and classes and it is similar to situation described in figure (18).

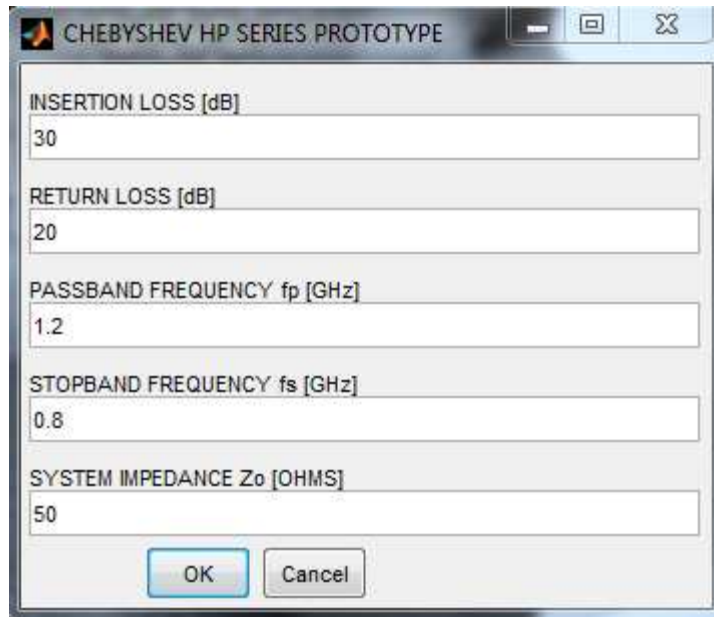


Figure 21 Second Step: Input data for Chebyshev HP Series Prototype.

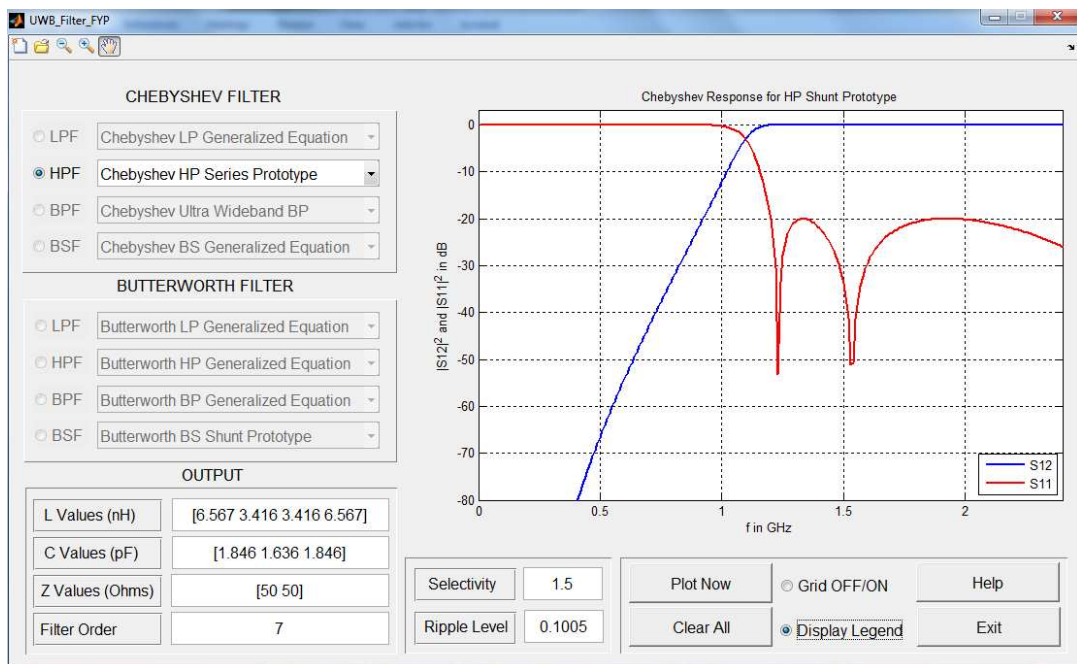


Figure 22 Final Step: Display of Frequency Response of Chebyshev HP Series

Prototype.

In figure (22), the corresponding values of reactive elements and the impedances (for both source and load) are displayed in their respective field. They are all displayed in array form. The user will need to identify the individual elements using this analogy:

$$\begin{aligned} L \text{ (nH)} &= [6.567 \ 3.416 \ 3.416 \ 6.567] \\ &= [L_1, L_3, L_5, L_7] \end{aligned}$$

Thus $L_1 = 6.567 \text{ nH}$, $L_3 = 3.416 \text{ nH}$, $L_5 = 3.416 \text{ nH}$ and $L_7 = 6.567 \text{ nH}$.

$$\begin{aligned} C \text{ (pF)} &= [1.846 \ 1.636 \ 1.846] \\ &= [C_2, C_4, C_6] \end{aligned}$$

Hence $C_2 = 1.846 \text{ pF}$, $C_4 = 1.636 \text{ pF}$ and $C_6 = 1.846 \text{ pF}$.

And $Z = [50 \ 50] = [Z_s, Z_L]$, thus $Z_s = 50\Omega$ and $Z_L = 50\Omega$

4.1.2.1.3 Chebyshev Band Pass Filter

As an illustration for BPF, the response and the important parameters can be obtained for capacitively coupled BPF. The following figures exemplify capacitively coupled circuit topologies.

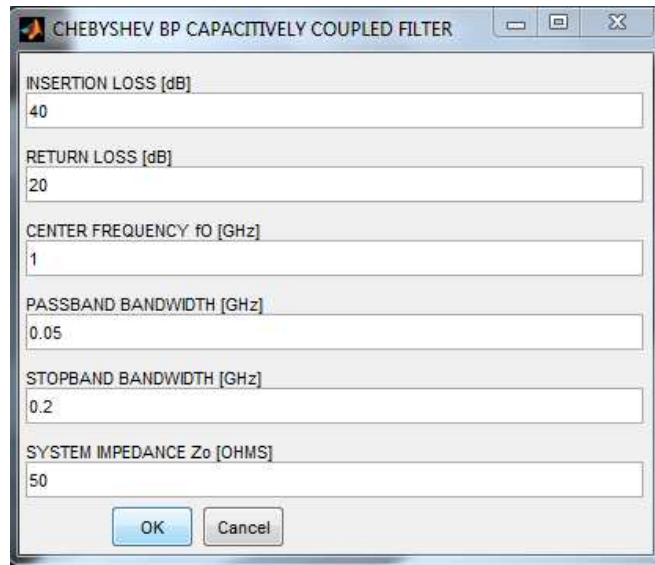


Figure 23 Second Step: Input data for Chebyshev Capacitively coupled BPF.

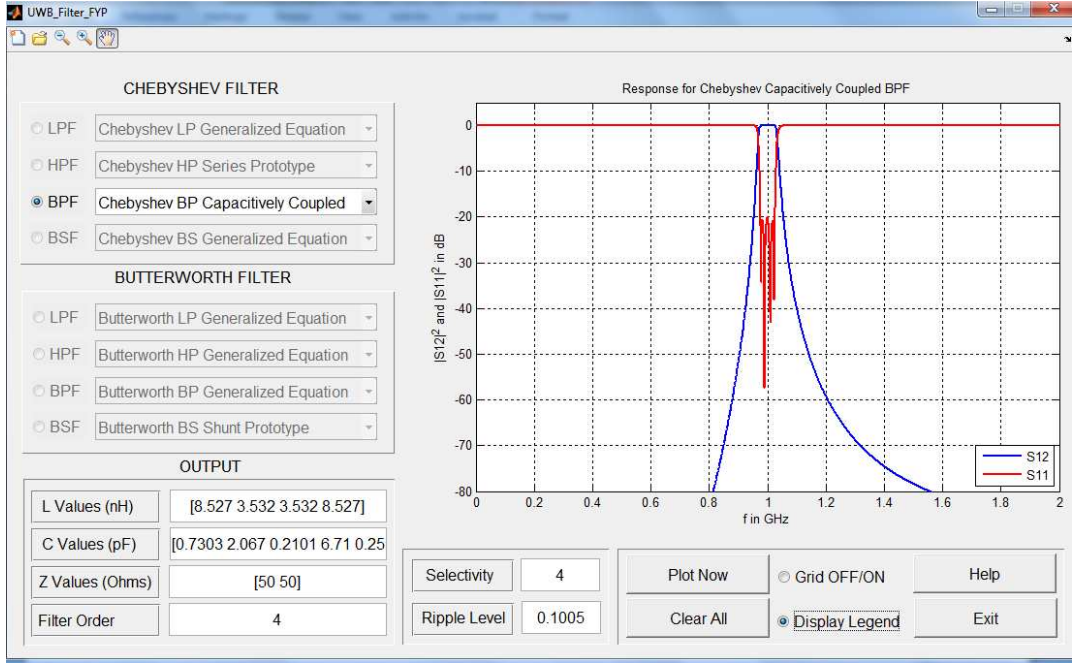


Figure 24 Final Step: Frequency Response of Chebyshev HP Series Prototype.

From figure (24), the impedances for both source and load are $Z_s = 50\Omega$ and $Z_L = 50\Omega$. The reactive elements are also portrayed in their respective field. By identification:

$$C \text{ (pF)} = [0.7303 \ 2.067 \ 0.2101 \ 6.71 \ 0.251 \ 6.71 \ 0.2101 \ 2.067 \ 0.7303]$$

$$= [C_{01}, C_{11}, C_{12}, C_{22}, C_{23}, C_{33}, C_{34}, C_{44}, C_{45}]$$

Therefore

$$C_{01} = C_{45} = 0.7303 \text{ pF}$$

$$C_{11} = C_{44} = 2.067 \text{ pF}$$

$$C_{12} = C_{34} = 0.2101 \text{ pF}$$

$$C_{22} = C_{33} = 6.71 \text{ pF}$$

$$C_{23} = 0.251 \text{ pF}.$$

And

$$L \text{ (nH)} = [8.527 \ 3.532 \ 3.532 \ 8.527]$$

$$= [L_{11}, L_{22}, L_{33}, L_{44}]$$

$$\text{Thus } L_{11} = L_{44} = 8.527 \text{ nH and } L_{22} = L_{33} = 3.532 \text{ nH}$$

These reactive element values, source and load impedances can be used to construct the corresponding microwave circuit for the filter.

It is also important to illustrate the case of UWB band-pass filter as it is one of the latest microwave filter topology that has been integrated for the first time and only in this filter design tool. The illustration for this case is presented as follow:

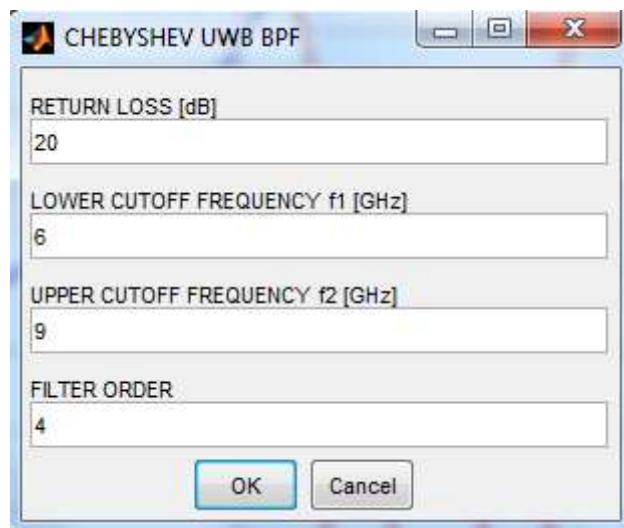


Figure 25 Second Step: Input data for Chebyshev Capacitively coupled BPF.

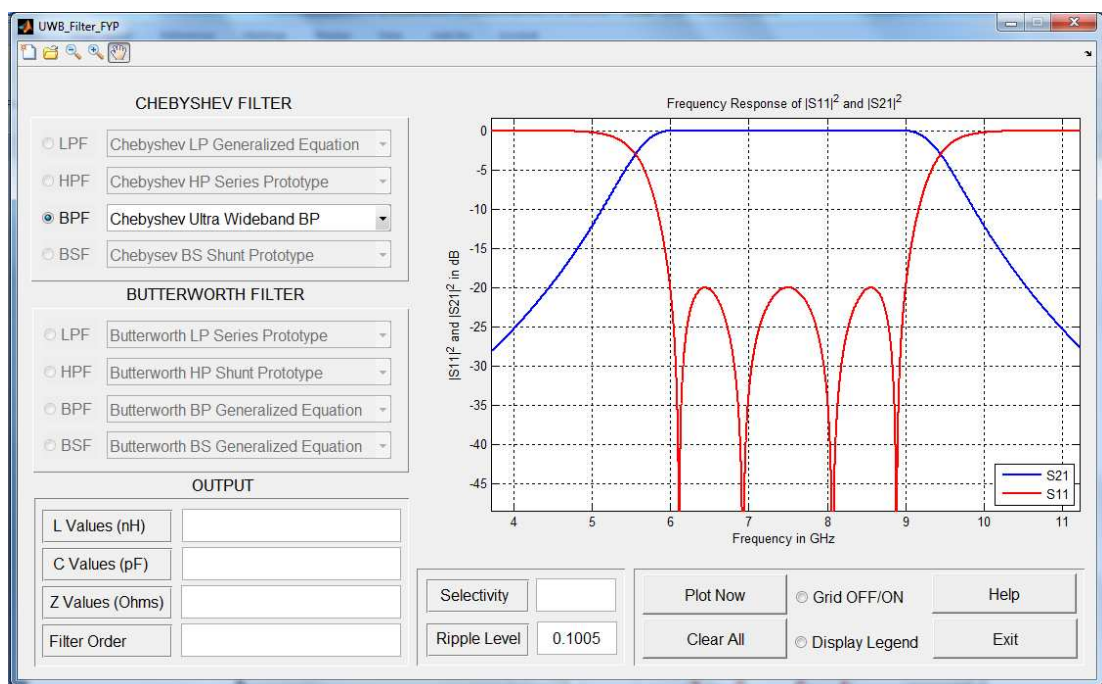


Figure 26 Final Step: Frequency Response of 4th order UWB BPF.

4.1.2.1.4 Maximally Flat Band Pass Filter

Likewise, when the user intend to design microwave filter using the maximally flat response, the procedures are almost the same with equal-ripple response demonstrations. For example, to design a band-stop filter using Butterworth response, the following steps are followed (assuming that the filter type and class were selected).

Figure 27 Second Step: Input data for Butterworth BSF.

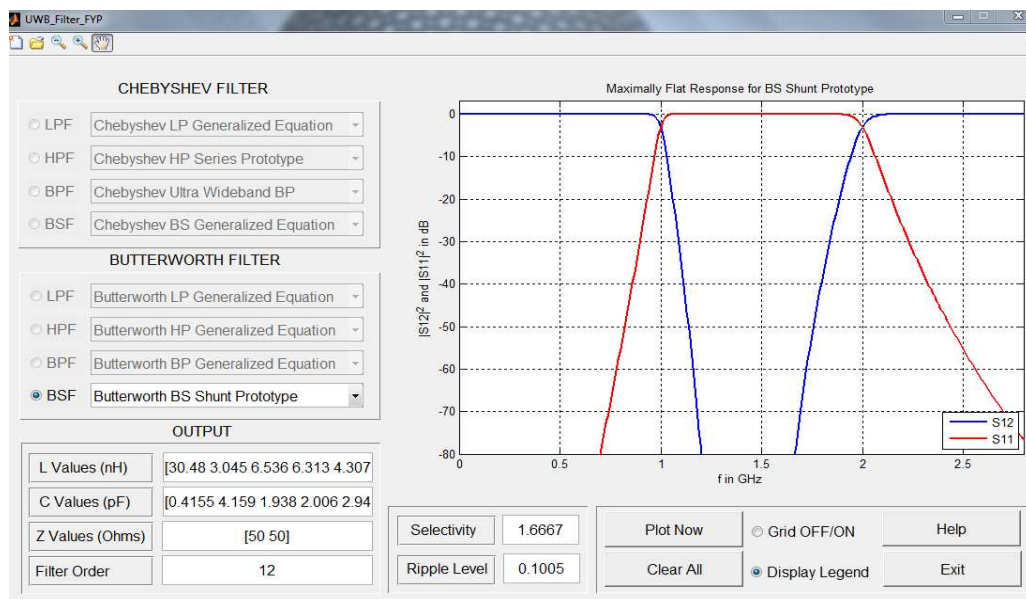


Figure 28 Final Step: Frequency Response of Maximally flat BSF.

The individual reactive element values for the linear microwave circuit can be obtained by using this following identification.

$$L(nH) = [30.48 \ 3.045 \ 6.536 \ 6.313 \ 4.307 \ 7.89 \ 4.013 \ 7.352 \ 5.015 \ 4.844 \ 10.4 \ 1.039]$$

$$= [L_1, L_2, L_3, L_4, L_5, L_6, L_7, L_8, L_9, L_{10}, L_{11}, L_{12}]$$

Thus $L_1 = 30.48 \text{ nH}$, $L_2 = 3.045 \text{ nH}$, $L_3 = 6.536 \text{ nH}$, $L_4 = 6.313 \text{ nH}$,
 $L_5 = 4.307 \text{ nH}$, $L_6 = 7.89 \text{ nH}$, $L_7 = 4.013 \text{ nH}$, $L_8 = 7.352 \text{ nH}$,
 $L_9 = 5.015 \text{ nH}$, $L_{10} = 4.844 \text{ nH}$, $L_{11} = 10.4 \text{ nH}$ and $L_{12} = 1.039 \text{ nH}$.

$$C(pF) = [0.4155 \ 4.159 \ 1.938 \ 2.006 \ 2.94 \ 1.605 \ 3.156 \ 1.723 \ 2.525 \ 2.614 \ 1.218 \ 12.19]$$

$$= [C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8, C_9, C_{10}, C_{11}, C_{12}]$$

Hence $C_1 = 0.4155 \text{ pF}$, $C_2 = 4.159 \text{ pF}$, $C_3 = 1.938 \text{ pF}$, $C_4 = 2.006 \text{ pF}$,
 $C_5 = 2.94 \text{ pF}$, $C_6 = 1.605 \text{ pF}$, $C_7 = 3.156 \text{ pF}$, $C_8 = 1.723 \text{ pF}$,
 $C_9 = 2.525 \text{ pF}$, $C_{10} = 2.614 \text{ pF}$, $C_{11} = 1.218 \text{ pF}$ and $C_{12} = 12.19 \text{ pF}$.

And $Z = [50 \ 50] = [Z_s, Z_L]$, thus $Z_s = 50\Omega$ and $Z_L = 50\Omega$

4.1.2.2 Hallmarks of the graphical user interface

The major feature of this GUI is its simplicity. It is a straightforward software tool for microwave filter design that can help students and learners to grasp the concept of microwave engineering. In addition, it takes less than a minute to display an impeccable filter response that can be the basis and the framework for a scientific and technical discussion.

The key characteristics and features of the proposed GUI are presented in the table below.

Table 3 Major features of the GUI and its comparison with the existing design tools.

Features	Classical tools	Proposed tool
Conventional filter topologies	✓	✓
Modern filter topology		✓
2-D response simulation	✓	✓
2-D response emulation		✓
Easy to use, good for sophomores		✓
Stand-alone capability	✓	✓

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

The developed graphical user interface for microwave filter design can successfully run on both computers with MatLab installed and on PCs with no MatLab software. For the latter case, the stand-alone GUI can run with the help of MatLab Compiler Runtime (MCR) that carries the necessary library required to run stand-alone MatLab applications. The GUI environment is easier for users to comprehend and familiarize themselves with. This modest GUI design can help the end-users to create impeccable and professional microwave filters even if they do not have a high level of expertise in the area of filter design tools, simulator or advanced design systems.

The proposed graphical user interface is integrated with both modern and conventional microwave filter topologies. This software tool can significantly help in reducing the training time and cost. It is the right and appropriate software tools for microwave education for both industries and educational institutions.

For future research works in this area, the graphical user interface can be developed using another approach. This approach can be directed to the use of object oriented programming such as java GUI programming, QT5 or VB.Net to create a dynamic synthesis tool for microwave filter design. From this approach, the possibility of integrating circuits and systems (such as schematic diagrams, functional blocks, nonlinear components, symbolic variables ...) can also be explored.

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