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DESIGN AND SIMULATION OF A 4TH ORDER HIGH FREQUENCY BANDPASS FILTER FOR RADAR COMMUNICATION SYSTEMS

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ABSTRACT

Electronic filters are frequency-selective circuits design to permit specific range of frequencies to pass through the electronic circuit and attenuate (or reject) others. These circuits are design to have different construction for different applications such as low-pass filter (LPF), high-pass filter (HPF), band-pass filters (BPF) and band-reject filter (BRF). In this paper, we deign and simulate a bandpass filter based on fourth order Butterworth filter design method that operate at 3.6 MHz intermediate frequency. The results obtained by implementing and simulating the original and adjusted design using AWR software showed that the bandpass filter operate within the desired design requirement with the anticipated -3 dB bandwidth of 800 kHz with the original design values, while approximately 700 kHz was obtained with the adjusted design due to practical components availability and limitations. Overall, the frequency responses of the designed and simulated filter in both original and adjusted design operating at 3.6 MHz and 3.4 MHz respectively, indicate an excellent output frequency response with the flat amplitude response of a Butterworth filter as well as compromised between attenuation characteristic and group delay.

1. Introduction

Electronic filters are an essential component in any communication system as frequency-selective circuits that allow specific frequencies to pass and attenuate (reject) others [1]. These have different construction for different applications such as low-pass filter (LPF), high-pass filter (HPF), band-pass filters (BPF) and band-reject filter (BRF) [2]. These are classified based on the frequencies they pass (allow) or reject (attenuated). BPF is the mostly use component in RF communication circuits with dual-band characteristic being the popular critical components in multi-service wireless communication and/or wideband communication systems [2]-[6]. The breakpoint between the passband and reject-band is normally taken to be the frequency at which the pass-band curve (response) falls off -3-dB power cut-off or -6-dB voltage [7].

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The signal time delay in the BPF at the input of Analogue Digital Conversion (ADC) is the cause of the dynamic error, which is added to the static error and reduces effective bit depth of the ADC [8]-[10]. This paper presents the design, implementation by simulation of band-pass filter (BPF) using microwave office AWR software. This BPF was applied at the output of the Frequency Modulated Continues Wave (FMCW) RADAR system before and after amplifications. The BPF was used in this case to select or pass only the intermediate or frequency (IF or f_b) of the radar, which the radar use to detect object at specific range. All other signals outside the passband (unwanted) were rejected or attenuated. The output of this filter is usually amplified before the transmission. Moreover, the design technique followed the Butterworth design method for nth order (elements) bandpass filter.

However, the construction of BPF combined a LPF and HPF configurations [11]. This also combines the advantage of both high and low pass configurations that are merged to form a range of frequencies called passband permitted by the BPF. In this paper, the same methodology was employed to design and simulate a 4th order high frequency (HF) BPF that allow 3.4 MHz to 3.6 MHz signals for application in FMCW RADAR system.

2. Bandpass Filter Design Methodology

The design of inductor-capacitor (LC) filters for microwave circuits is presented in its mathematical form to calculate and determine the necessary parameters of the filter being design [3,12]. The RF filter design normalised the prototype low-pass filter (LPF) transformed into a BPF. However, use of that design approach give room for optimizing the design, the design approach followed assumes equal (matched) input and output impedances [4,13]. The design procedure for this filter followed the Butterworth filter design method and processes. This procedure is summarized and elaborated below.

1. The IF frequency for the filter is calculated.
2. Selectivity or quality factor Q was calculated to help set the limit of Q for better performance.
3. Performing the transformation of the BPF requirements to an equivalent LPF requirement
4. Determine the order of the filter, *n* that satisfied the design requirements.
5. Obtain the corresponding LPF prototype circuit.
6. Transform the LPF circuit into a BPF configuration.
7. Scale both frequency and impedance of the BPF configuration
8. Design implementation by simulation.

These steps are demonstrated in this section starting with the IF frequency calculation of the filter under design in this case BPF using equation (1).

$$IF = \frac{(2 * \Delta F * \Delta T)}{T_m} ------ (1)$$

Where ΔT is the time delay, $\Delta F = 10\,MHz$ is the frequency deviation from the modulating frequency f_m, and T_m is the period of the f_m. The modulating frequency, f_m is also called the intelligence signal and was given as *400kHz* in this design. These parameters are computed using equations (2) and (4).

$$\Delta T = \frac{L}{v_p} ---------- (2)$$

where L is the length of the transmission line or cable goiven as *100 m* and the propagation velocity, v_p given by

$$v_p = \frac{c}{\sqrt{\varepsilon_r}} ---------- (3)$$

where $c = 3x10^8\ m/s$ is the speed of light in vacuum and $\varepsilon_r = 1.8$ the dielectric constant of the transmission line. Therefore, using equations (2) and (3) with given values of c, L and ε_r, we obtained $v_p = 2.24x10^8\ ms^{-1}$ and $\Delta T = 4.46x10^{-7}s = 446\ ns$. Finally, IF is calculated by finding the value of $T_m = 2.5x10^{-6}\ s = 2.5\ \mu s$ using equation (4).

$$T_m = \frac{1}{f_m} - - - - (4)$$

Thus, *IF* is determined using equation (1) from the calculated design parameters obtained.

$$IF = \frac{(2 * \Delta F * \Delta T)}{T_m} = \frac{(2 * 10x10^6 * 446x10^{-9})}{2.5x10^{-6}} = 3.568x10^6 \cong 3.6\ MHz$$

Table I: Design Parameters and values

IF (Hz)	ΔF(Hz)	$T_m\ (s)$	$\Delta T\ (s)$	ε_r	$v_p(ms^{-1})$	L (m)
$3.6\ x\ 10^6$	$10\ x\ 10^6$	$2.5\ x\ 10^{-6}$	$4.46x10^{-7}$	1.8	$2.24x10^8$	100

Moreover, if the BPF is designed for RADAR system application and the resolution R for the RADAR is known, the $IF = f_b$ and $\Delta T = T_d$ can be determine using equation (5) and (6).

$$IF = f_b = \frac{(2 * \Delta F * \Delta T)}{T_m} = \frac{(2 * \Delta F * T_d)}{1/f_m} = \frac{(4 * \Delta F * f_m R)}{c} - - - - - - (5)$$

$$\Delta T = T_d = \frac{2R}{c} - (6)$$

where T_d is the time delay and R is the RADAR resolution (target) range. In this case, the beat frequency is *to-and-forth* path, the reason for multiplying by 4, for one path need to multiply by 1/2.

Another important parameter in filter design especially the BPF design is the selectivity or quality factor Q. The selectivity of the filter under design was calculated by taking into consideration the limitation that the selectivity be less than fifteen (Q<15). Therefore, IF and f_m were carefully determined to give Q value within this specified limit. Due to component availability consideration and to avoid filter with high order, equation (7) was used to compute the required Q value.

$$Q = \frac{IF}{2 * f_m} - - - - - - - (7)$$

The value of $Q = 4.5 \cong 5$ was obtained using the calculated value of $IF = 3.6\ MHz$ and $f_m = 400\ kHz$. Although the high value of Q means high selectivity, narrow band, and flat response [11]-[13]. This must be avoided due to the constraint in components availability for implementation of this design. The required order or number of elements, n and LPF prototype circuit, that will satisfy the BPF requirements for having specific attenuation at bandwidth (BW) = $4 * f_m$ is determined using equations (8) to (11).

$$\frac{BW}{BW_o} = \frac{f}{f_o} = \frac{4f_m}{2f_m} = 2 - - - - - - - (8)$$

$$\frac{BW}{BW_o} = 2 \leftrightarrow BW = 2 * BW_o - - - (9)$$

Since we obtained the frequency ratio, $\frac{f}{f_o} = 2$ from equation (8), we can use the attenuation characteristics for Butterworth filter in figure 1 to choose the maximum (order) number of elements, n.

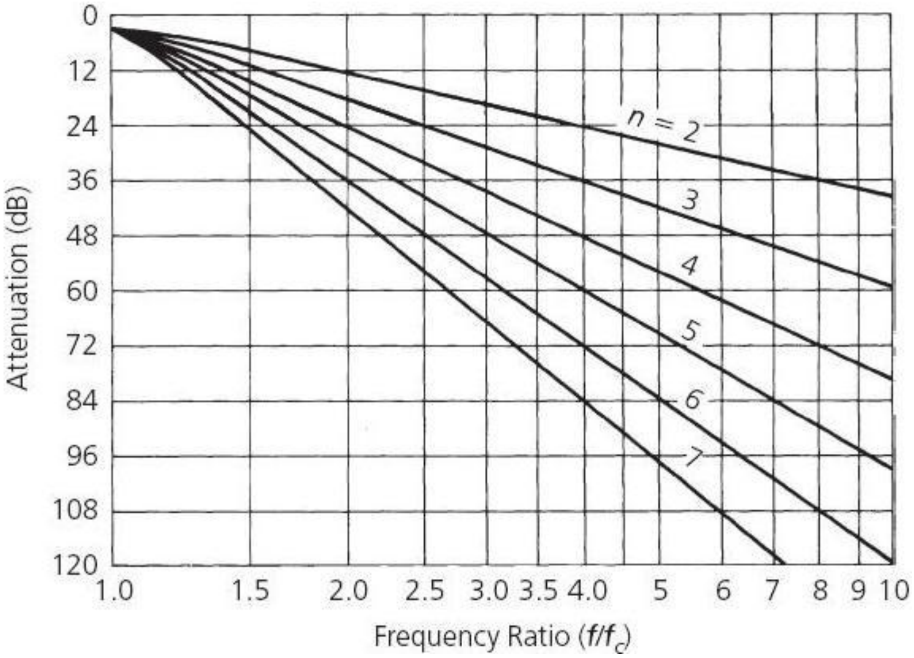


Figure 1: Attenuation Characteristics for Butterworth Filter

Figure 1 shows that $n = 4$ and it correspond to an attenuation of *-24 dB,* which means a LPF prototype of at least 4-elements when transformed to BPF will give such attenuation at the specified bandwidth [12]. Therefore, the filter must be down by at least *-24 dB* at twice the *3 dB* bandwidth (2*BW_{3dB}) or cut-off frequency and a minimum of 4-elements filter is required to meet this design goal. This required attenuation was also proved using the attenuation equation, the specified requirements, and the value of *n* obtained [12].

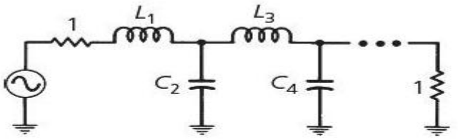
$$A_{dB} = 10\log\left\{1 + (\frac{f}{f_o})^{2n}\right\} - - - - - (10)$$

The BW of this filter is difference between the lower (f_l) and higher (f_h) cut-off frequencies [11]. Adjusting these *-3 dB* cut-off frequencies of the high pass filter (f_l) and the low pass filter (f_h) can be use to obtain the appropriate BW_{-3dB} for the BPF using equation (11).

$$BW(Hz) = f_h - f_l - - - - - - - - - (11)$$

After obtaining the value of the order *n*, the next step is to choose the LPF prototype and transform it to BPF configuration which is then scale using the impedance, *R* and cut-off frequency (f_c) with the LPF prototype and the normalized values given in Table I. The BPF configuration is then scaled in both *R* and f_c using the equations for parallel and series branches given by equations (12) to (15), in which the required values for the resonant (*LC*) circuit branches were obtained [11,12]. For a Butterworth filter of n^{th} order, f_c ,a source and load resistance *R*, the filter components values are determined using equations (12) to (15).

Table II: LPF Corresponding Normalised LC Values

2	1.414	1.414					
3	1.000	2.000	1.000				
4	0.765	1.848	1.848	0.765			
5	0.618	1.618	2.000	1.618	0.618		
6	0.518	1.414	1.932	1.932	1.414	0.518	
7	0.445	1.247	1.802	2.000	1.802	1.247	0.445
n	L_1	C_2	L_3	C_4	L_5	C_6	L_7
							

Parallel-resonant branches

$$C = \frac{C_n}{2\pi RB} ------ (12)$$

$$L = \frac{RB}{2\pi f_c^2 L_n} ------ (13)$$

Series-resonant branches

$$C = \frac{B}{2\pi f_c^2 R C_n} ------ (14)$$

$$L = \frac{R L_n}{2\pi B} ---------- (15)$$

where R is the load impedance, $B = BW_{3dB}$ is the *3 dB* bandwidth of the filter, f_c is the centre/cut off frequency, C_n is the normalised capacitor value, and L_n is the normalised inductor value of the BPF under design. Equations (12) to (15) were used to scale the values of series and parallel resonant (LC) branches using $BW_{3dB} = 2 * f_m = 800kHz$, $f_c = IF = 3.6\, MHZ$ and $R = 50\Omega$.

Table II gives the normalised values found to be $L_1 = L_3 = C_1 = C_3 = 1.00$ and $L_2 = C_2 = 2.00$. Thus, by substituting these values for the unknowns in the scaling equations (12) to (15) the corresponding value for the BPF circuits were found to be $L_1 = L_3 = 9.947\, \mu H$, $L_2 = 2.456\, \mu H$, $C_1 = C_3 = 196.488\, pF$, and $C_2 = 7.958\, nF$. Figure y1 give the resulting circuit for a 4th order BPF with f_c *=3.6 MHz* and an impedance (Z_1 and Z_2) of *50 Ω*.

The circuit implementation shown in figure 2 was simulated and found to give the desired response of a Butterworth filter shown by the result in figure 4. The output response in figure 4 will be analyse in the results section.

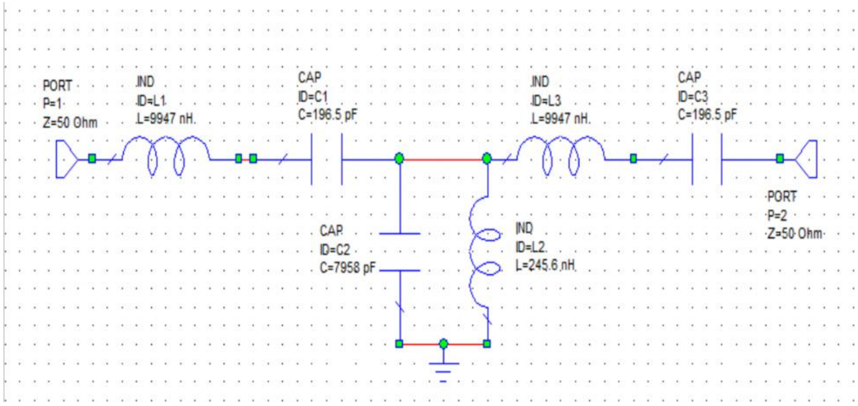


Figure 2: Simulated Circuit Diagram of the Transformed LPF to BPF

However, the components values need to be adjusted to implement this design practically using real components. The calculated values during the design cannot be obtained from the available components at the time for practical circuit e design implementation. These values of the LC’s were approximated to the nearest available and practical values with $L_1 = L_3 = 10\,\mu H$, $L_2 = 220\,nH$, $C_1 = C_3 = 220\,pF$, and $C_2 = 10\,nF$. These adjusted values as shown in the adjusted circuit diagram in figure 3 were found to give about similar output response as the originally calculated values as shown in figure 5. This output response of the adjusted design implementation in figure 3 will be analyse in the results section.

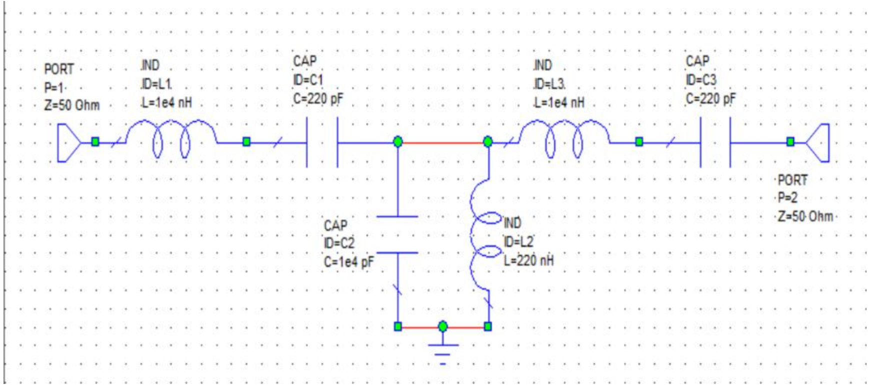


Figure 3: Adjusted Schematic Diagram of the BPF with Approximate LC Values

3. Results Discussion and Analysis

The original BPF was designed to achieve a $BW_{3dB} = 800kHz$ with an *IF = 3.6 MHz*, however, an adjustment was required due to practical components availability constraint. This led to adjusted value of *IF = 3.4 MHz* for practical implementation of the circuit form the original design. Frequencies above and below the IF were attenuated as shown by the output responses in figure 4 and 5. Although an ideal design of the filter could not be achieved in practice due to practical limitations such as practically components availability and internal factors due to circuit functions. These limitations led to external and internal constraint when implementing the design for practical purpose. Acceptable results close to the ideal for practical purpose was obtained. These results from the output responses of the designed and implemented BPF in both original and adjusted design were found to be excellent as shown in figure 4 and 5.

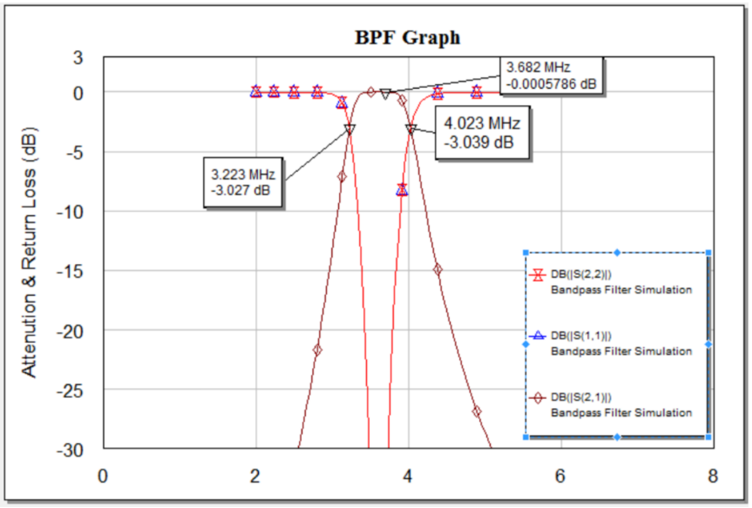


Figure 4: Simulated Transformed LPF to BPF Output Response

Observing figures 4 and 5 showed the output responses of the original and adjusted designs are identical with slightly different *IF* value. This slight difference in *IF* values is due to the approximation of the components (LC) values. These output responses in figures 4 and 5 have almost the same upper side (f_h) and lower side (f_l) frequencies at *-3 dB*. However, the anticipated BW_{3dB} of 800 kHz was found with the calculated values for the filter design considering f_h *=4.023 MHz and* f_l *=3.223 MHz* as shown in figure 4. Also, approximately a BW_{3dB} of 700 kHz was obtained when the adjusted values were used in the simulation considering f_h *=3.75 MHz and* f_l *=3.068 MHz* as shown in figure 5. Thus, the original design was able to achieve 100% the required BW_{3dB} while the adjusted design was able to achieve 88% of the required bandwidth. As shown in table III, the ideal situation (original design) might not be realistic in practice due to the limitations in the real circuit such as soldering, components value changes due to excess heating, loss in the cables and along the path, loose connection, and external interference. Therefore, these results from the simulation were excellent, appreciable, and acceptable. The frequency responses of this designed BPF showed a maximally flat amplitude response of a Butterworth filter, this is an excellent compromise between attenuation characteristic and group delay. The group delay on the right-hand side of output responses in figures 4 and 5 remained flat near and above cut-of frequencies of *3.6 MHz* and *3.4 MHz* respectively. However, data communications can become degraded in Butterworth filters due to the exhibition of ringing in it step response. At f_c in figures 4 and 5 showed an attenuation at about *-3 dB* was observed. Attenuation at *-3 dB* is expected to satisfy one of the Butterworth filter design requirements [10,12,13].

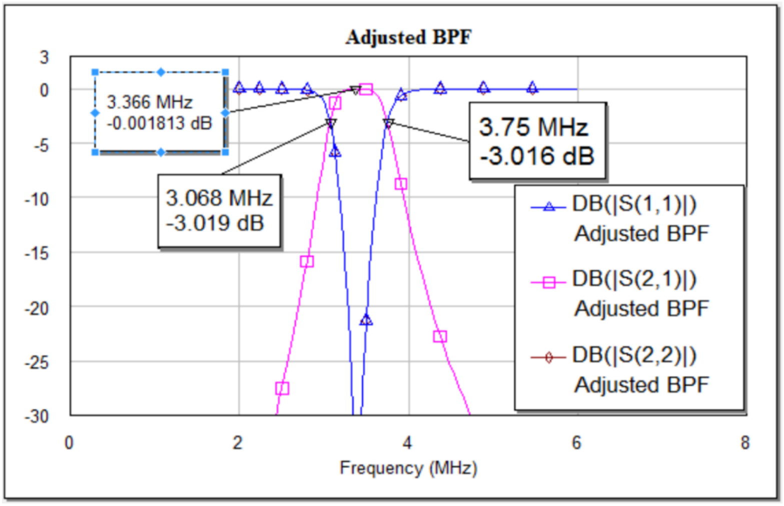


Figure 5: Adjusted Output Response of the BPF with Approximate LC Values

Table III shows the IF value changed from *3.6 MHz* to *3.4 MHz* due to the component's values approximation as well as LC elements dependency on frequency. Therefore, the change in the values of the elements influence the frequency and vice versa. As noticed from the output response of both the originally calculated values of L's and C's and the adjusted values, the responses are almost the same at *-3 dB.* Although there was slight change in the IF frequency the response remained almost identical even with the adjustment in resonant (LC) values, which shows the same performance is obtained when the design is implemented in practice with real and available components at the time.

Table III: Summarised Results of Original and Adjusted Design

Design	***IF (MHz)***	BW_{3dB}(kHz)	f_h (MHz)	f_l (MHz)	**Q-Factor**
Original	3.6	800	*4.023*	3.223	4.52
Adjusted	3.4	700	*3.75*	3.07	4.25

1. Conclusion

In this article, a step-by-step procedure of BPF designed to operate at *3.6 MHz* simulation using Butterworth filter design method was presented and implemented. The design was implemented using simulation of both the original and the adjusted designs. The results of the simulation were given in the form of frequency output response with the reflection and transmission coefficients in the form of scattering parameters (s-parameters) to compare the transmission and reflection of the signal within the pass band. The output frequency responses of the designed BPF indicated an excellent result with the flat amplitude response of a Butterworth filter as well as compromised between attenuation characteristic and group delay. The design was able to achieve the required and acceptable BW_{3dB} at specific cut off frequencies. The future work will focus on practical implementation and testing of the adjusted design using available components and equipment. This would allow us to verify and validate the performance of the design and the results obtained from the simulation.

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