Design of Butterworth Band-Pass Filter

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Abstract

This paper presents a high order filter for the Butterworth filters up to 8^{th} and 9^{th} order. The higher order filters are formed by using the combination of second and third order filters. While designing the Band-Pass Butterworth filter, four parameters need to be specified such as Ap (dB attenuation in the pass band), As (dB attenuation in the stop band), fp (frequency at which Ap occurs) and fs (frequency at which As occurs). The design procedure involves two steps, the first step is to find the required order of the filter and the second step is to find the scale factor that must be applied to the normalized parameter values. The Band-Pass Butterworth filler is a combination between low pass and high pass For the low pass Butterworth filter, the value of a resistor that has been used are 100KΩ and the value of the capacitor is found by scaled inversely with the frequency and the selected resistor value. While for the high pass Butterworth filter, the value of a capacitor that has been used is 0.05μF and the resistor value is found by scaled inversely with the frequency and the selected resistor value. The Butterworth Band-Pass filler required to bypass certain band of interest while suppressing the frequency below and above than pass band. Two configurations design circuit was tested by using LTspice software.

Keywords: Ap, As, LTspice.

1. Introduction

A filter is a system that processes a signal in some desired fashion. A continuous-time signal or continuous signal of x(t) is a function of the continuous variable t. A continuous-time signal is often called an analog signal. A discrete-time signal or discrete signal x(kT) is defined only at discrete instances t=kT, where k is an integer and T is the uniform spacing or period between samples. There are two broad categories of filters which are an analog filter process continuous-time signals and a digital filter process discrete-time signals. The analog or digital filters can be subdivided into four categories, low pass filters, high pass filters, band stop filter and bandpass filters.There are a number of ways to build filters and of these passive and active filters are the most commonly used in voice and data communications[1]. The passive filters use resistors, capacitors, and inductors (RLC networks). To minimize distortion in the filter characteristic, it is desirable to use inductors with high quality factors (remember the model of a practical inductor includes a series resistance), however, these are difficult to implement at frequencies below 1 kHz due to the particularly non-ideal (lossy) as well as bulky and expensive. The active filters overcome these drawbacks and are realized using resistors, capacitors, and active devices (usually op-amps)[2]. The function of filters is to eliminate background noise, radio tuning to a specific frequency, direct particular frequencies to different speakers, modify digital images and remove specific frequencies in data analysis. The approximations to the ideal filter are the Butterworth filter.Chebyshev filter and Bessel filter. The Butterworth filter is a type of signal processing filter designed to have as flat a frequency response as possible in the passband. It is also referred to as a maximally flat magnitude filter. The frequency response of the Butterworth filter is maximally flat (has no ripples) in the passband and rolls off towards zero in the stopband.When viewed on a logarithmic Bode plot the response slopes off linearly towards negative infinity. A first-order filter's response rolls off at −6 dB per octave (−20 dB per decade) (all first-order lowpass filters have the same normalized frequency response). A second-order filter decreases at −12 dB per octave, a third-order at −18 dB and so on. Butterworth filters have a monotonically changing magnitude function with ω, unlike other filter types that have non-monotonic ripple in the passband and/or the stopband. Compared with a Chebyshev Type I/Type II filter or an elliptic filter, the Butterworth filter has a slower roll-off, and thus will require a higher order to implement a particular stopband specification, but Butterworth filters have a more linear phase response in the pass-band than Chebyshev Type I/Type II and elliptic filters can achieve.

2. Literature Review

Analog filters can be found in almost every electronic circuit. It used as for pre-amplification, equalization and tone control in audio systems. In communication systems, filters are used for tuning in specific frequencies and eliminating others. Digital signal processing systems use filters to prevent the aliasing of out-of-band noise and interference[3]. The data acquisition system signal chain that includes an analog filter is shown in Figure 1.

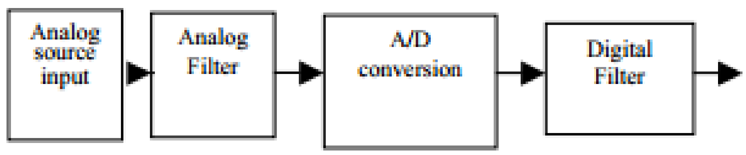


Figure 1. The data acquisition system signal chain can utilize analog or digital filtering techniques or combination of both

Bandpass filters play a significant role in wireless communication systems. Transmitted and received signals have to be filtered at a certain center frequency with a specific bandwidth. Figure 2 shows the Band-Pass filter specifications and frequency response.

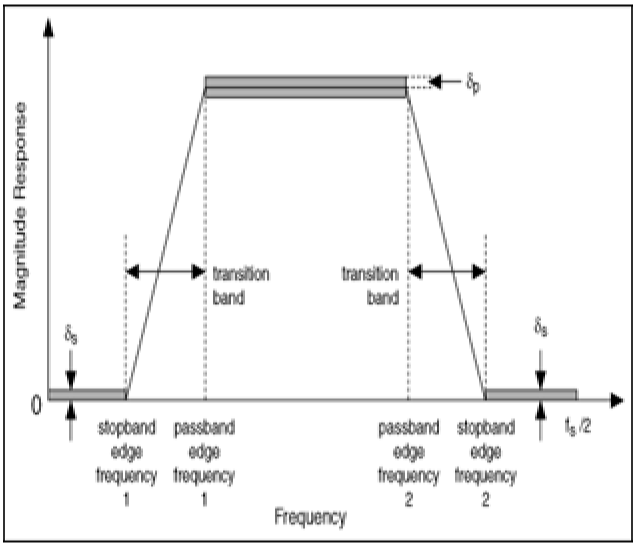


Figure 2. Band-Pass filter specifications and frequency response

The Butterworth filter is one type of signal processing filter design. It is designed to have a frequency response which is as flat as mathematically possible in the pass band. Butterworth solved the equations for two and four pole filters and showed how the latter could be cascaded when separated by vacuum tube amplifiers [3]. This made possible the construction of higher order filters in spite of inductor losses. Butterworth discovered that it was possible to adjust the component values of the filter to compensate for the winding resistance of the inductors. Figure 3 show the Frequency Response of the Butterworth filter.

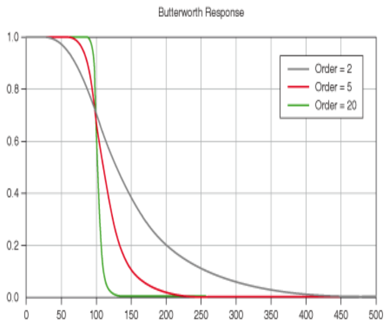


Figure 3. Frequency Response of the Butterworth filter

3. Methodology

This section of this paper will presented about the order and configuration of Butterworth band-pass filter by using LTSpice as the tools for the simulation and make a comparison between the mathematical theory and the simulation. A Butterworth filter must design according to specifications, to require being at 8^{th} and 9^{th} order order and fulfill the Ap (dB attenuation in the pass band), As (dB attenuation in the stop band), fp (passband frequency) and fs (stop band frequency).

Bandpass Butterworth filter need to design in this paper must have the characteristic as shown in figure 4.

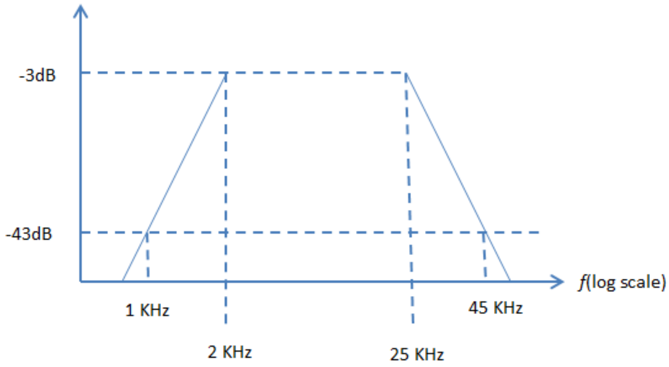


Figure 4: Gain versus Frequency

There were two different designs have been done that were Low Pass Filter and High Pass Filter. And then combine this design to build Butterworth Band Pass Filter. For the first design LPF, the calculations showed in appendix 1 and 2 and HPF shown in appendix 3 and 4.

So, the LPF circuit was designed as figure 5 below.

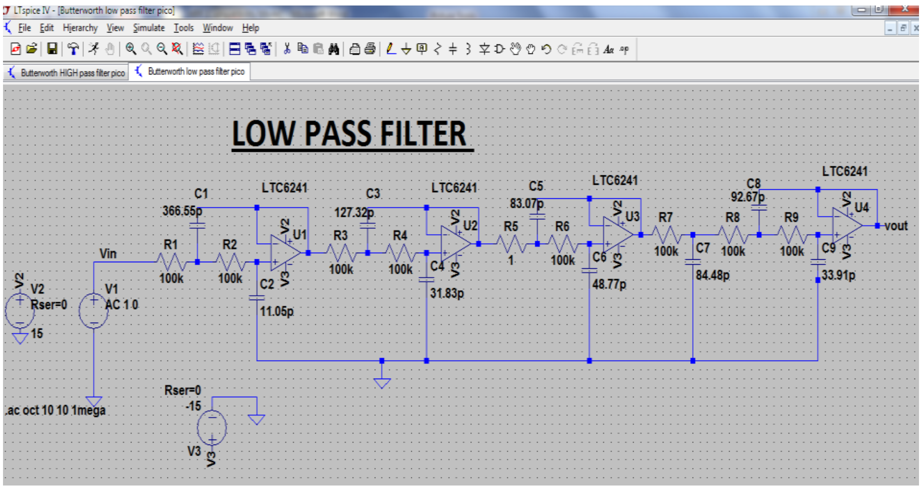


Figure 5. 9th order LPF Circuit Design using LT spiceIV

So, the HPF circuit was designed as figure 6 for 8th order by using 2nd order + 2nd order + 2nd order + 2nd order.

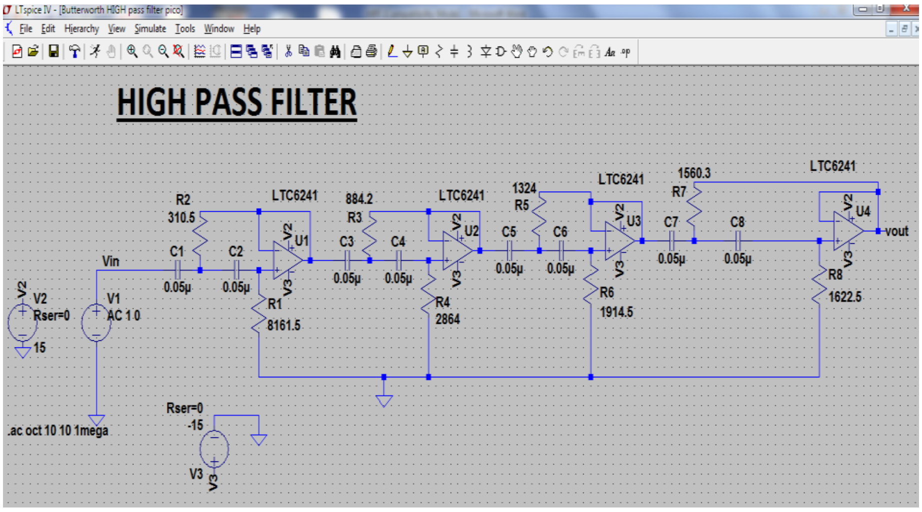


Figure 6. 8th order HPF Circuit Design using LTspice

Now combine this design, LPF and HPF is built Butterworth band-pass filter (BPF) circuit. So the figure of BPF is shown as figure 6. BPF is combining of LPF –HPF order as shown in figure 8.

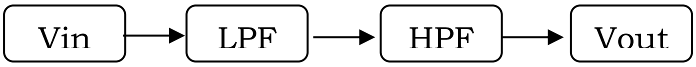


Figure 7. The order of combination of LPF and HPF

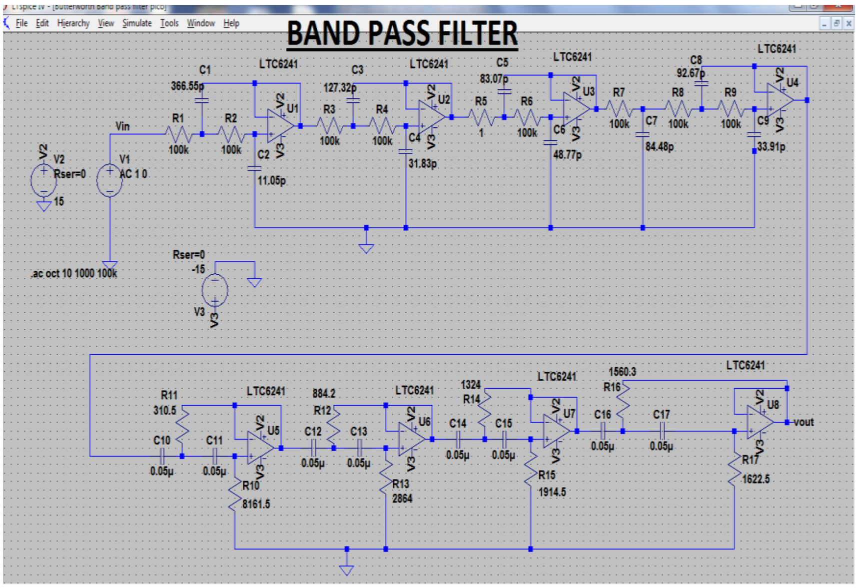


Figure 8. First Design of BPF Circuit combination of LPF-HPF

For the second design of LPF, the arrangement was as follows is by using 3rd order + 2nd order + 2nd order + 2nd order. The capacitance value is same but changes the orders in the circuit diagram. The circuit of second design is described in figure 9.

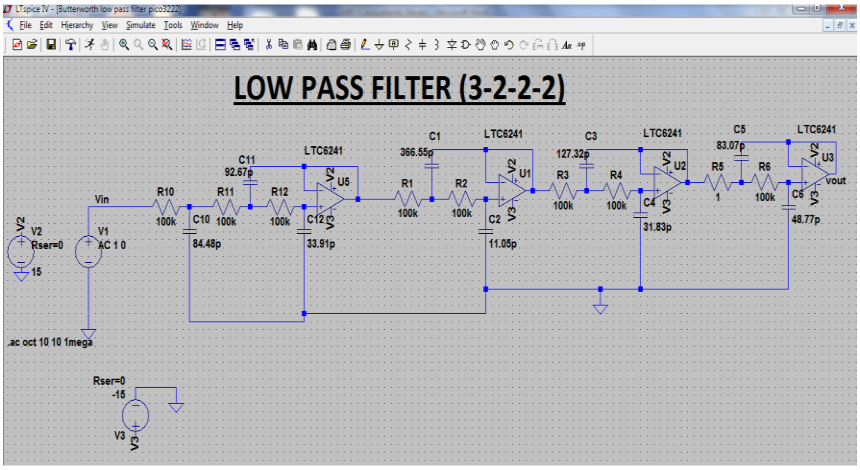


Figure 9. 8rd order LPF Circuit Design using LTspice

For HPF just do one design only because the order four stages of second order only, so if change the arrangement in circuit diagram it's remained same. Let's change the arrangement of BPF using this design as figure 10 and figure 11 show that circuit diagram of BPF with this combination.

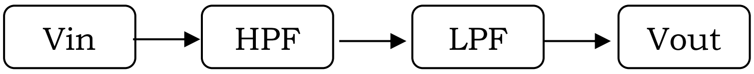


Figure 10. The order of combination of LPF and HPF

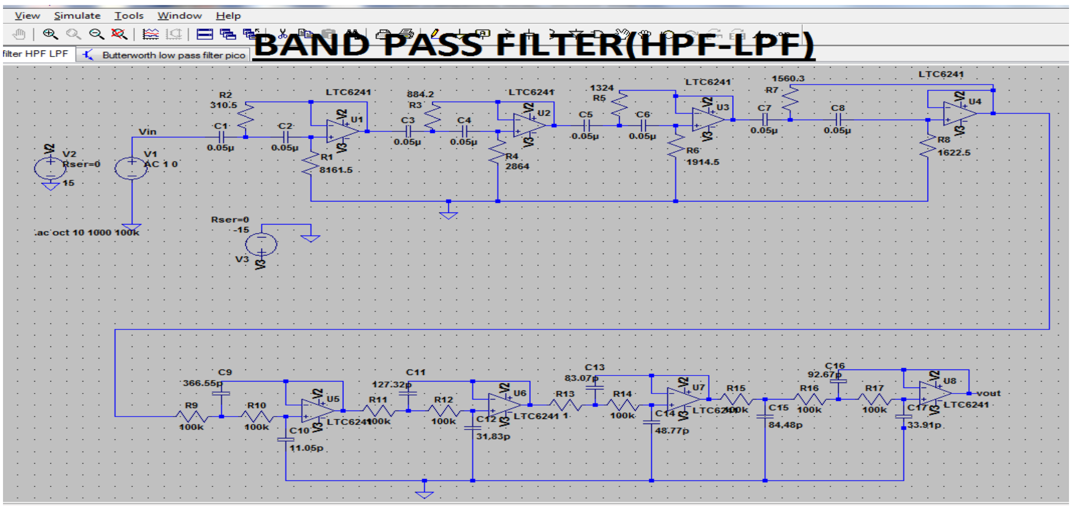


Figure 11. Second design of BPF Circuit combination of HPF-LPF

4. Results

In this section, the result of LPF, HPF and BPF circuit for both designs were represented using bode plot. The output of LPF at -3dB and -43dB are presented in figure 11. At -2.977dB get around 22.821kHz, by the way at -43dB fall at 43.9kHz.

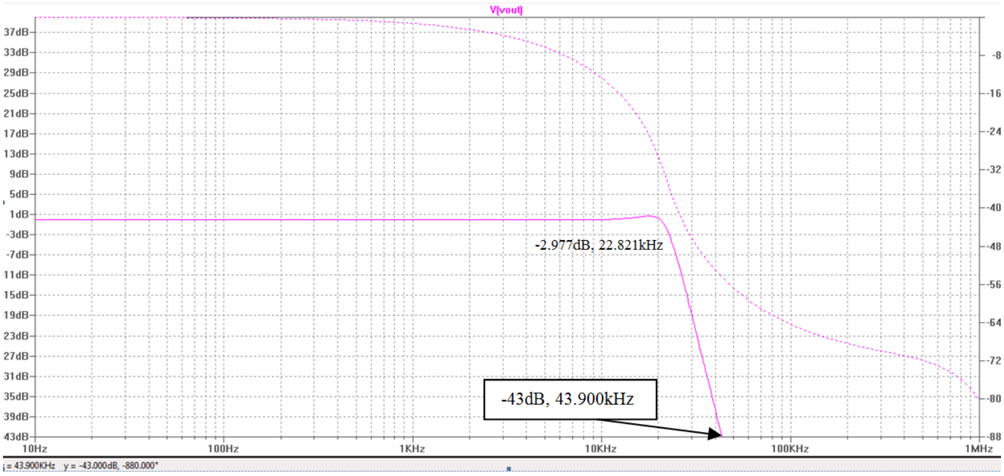


Figure 11. First Design of LPF Circuit at -3dB and -43dB

Figure 12 shows the design for HPF at -3db and -43dB. The output of HPF at -3dB and -43dB is 2kHz and 1.077kHz.

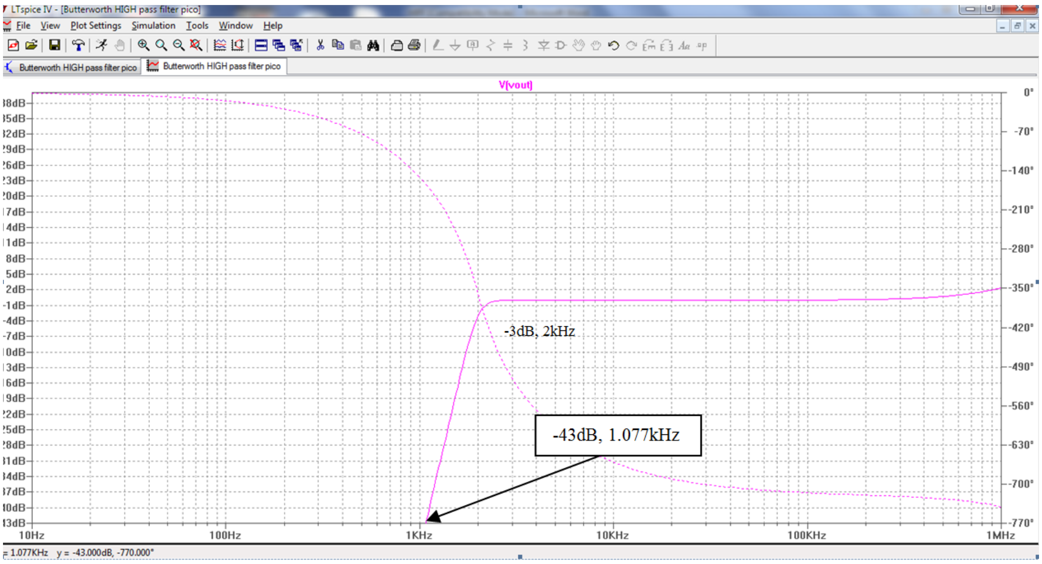
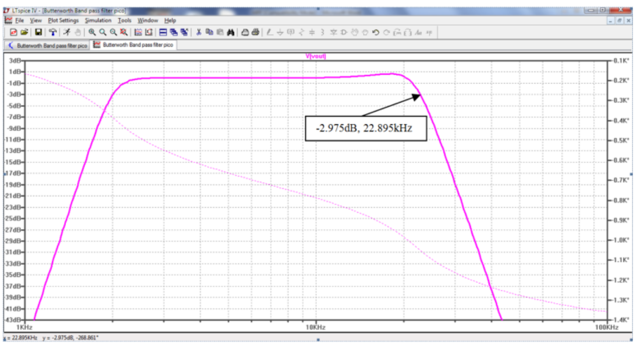
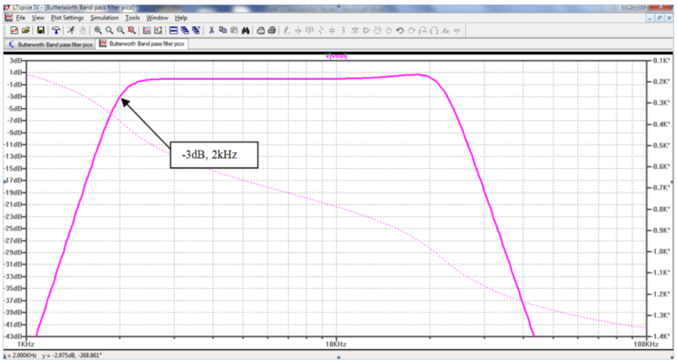


Figure 12. The Design of HPF Circuit at -3dB and -43dB

The combination of plotting the LPF and HPF will form the BPF. Figure 13a and 13b, shows the first design for BPF at -3dB. The combination of the LPF and HPF will form the BPF. Figure 14a and 14b, shows the first design for BPF at -43dB.

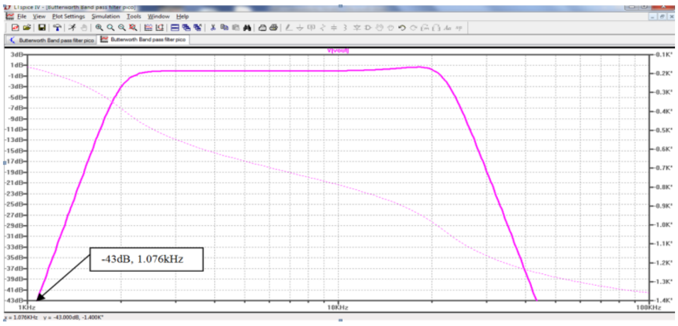


(a)

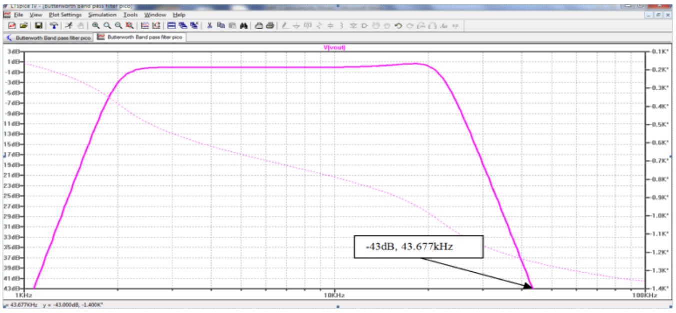


(b)

Figure 13. Design of BPF Circuit at -3dB (a) for LPF and (b) for HPF



(a)



(b)

Figure 14. Design of BPF Circuit at -43dB (a) for HPF and (b) for LPF.

Figure 15 and 16 shows the second design for LPF at -3dB and -43dB. For -3dB, frequency is 22.821kHz and 44.301kHz at -43dB.

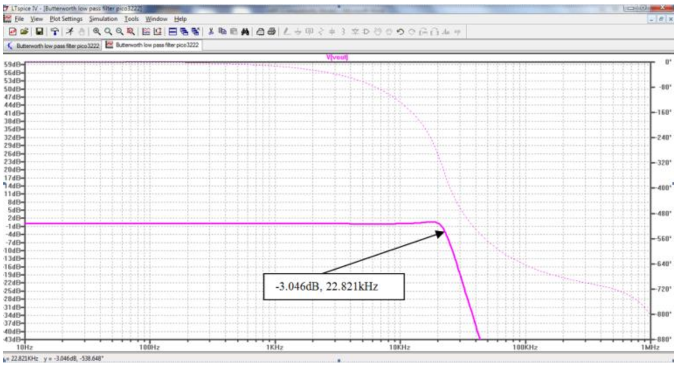


Figure 15. Second Design of LPF Circuit at -3dB

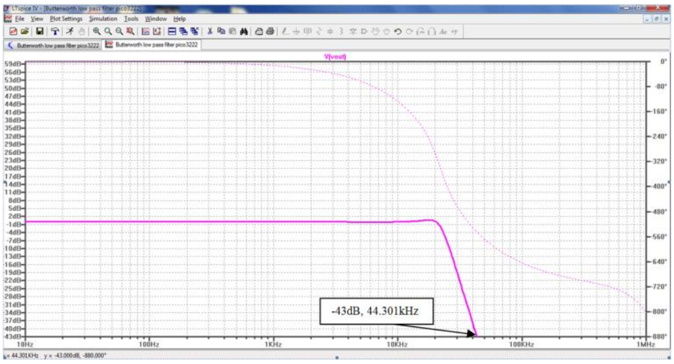
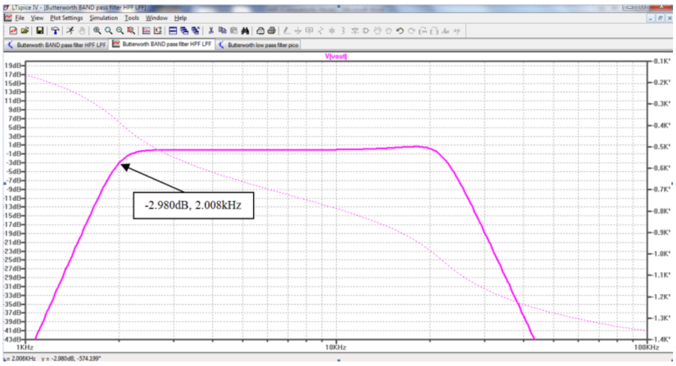
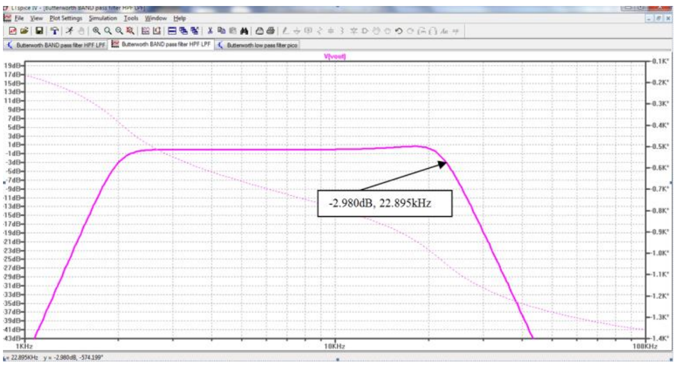


Figure 16. Second Design of LPF Circuit at -43dB

The combination of plotting the LPF and HPF will form the BPF. Figure 17a and 17b, shows the second design for BPF at -3dB combination of LPF and HPF.

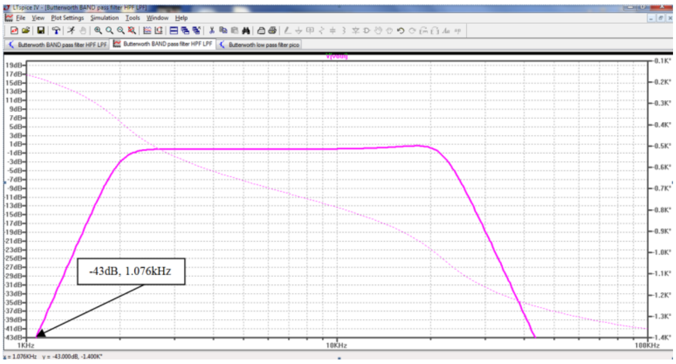


(a)

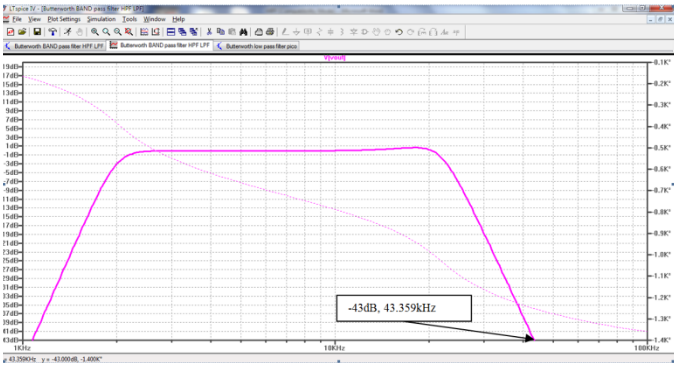


(b)
Figure 17. Second Design of BPF Circuit at -3dB for combination of HPF and LPF

The combination of plotting the LPF and HPF will form the BPF. Figure 18a and 18b, shows the second design for BPF at -43dB



(a)



(b)

Figure 18: Second Design of BPF Circuit at -3dB for combination of HPF and LPF

5. Discussion

Procedure of designing LPF and HPF is divided into two parts, the first part is finding the required order of the filter and the second part is finding the scale factor that must be applied to the normalized parameter value. After that, can design the LPF and HPF, to combine this two filter to build BPF. As a result, LPF can be designed in two combination of stage that is 2-2-2-3 and 3-2-2-2, its result at -3d and -43dB are almost same. From this can be concluded that the stage not influence the result. Anyhow, for HPF only has one design, combination of 2nd order only. Other than that, in this paper also discuss about the combination of the LPF and HPF to perform BPF. Therefore, there are two combination also in designing BPF where, LPF-HPF and HPF-LPF. The aim of this combination to get know is there have an influence on the performance of BPF. After the simulation is clearly shown that there is no difference between this combination orders. The performance of BPF is same for both combination stages.

6. Conclusion

Band-pass filter design using a Butterworth filter is presented in this paper. These circuits are composed using 8th and 9th order and two types of configuration which are 2-2-2-3 and 3-2-2-2 for 9th order and 2-2-2-2 for 8th order. Moreover the combination between LPF and HPF to form a BPF is design. There was two configuration have make to analysis the performance and influence in designing BPF. That is, LPF-HPF far first combination and HPF-LPF for second combination. As a conclusion, can be say that, there was no different with this combination, the results are almost same for both configuration. The BPF design in this paper have fulfill the characteristic given.

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Appendix 1

i. Low-pass filter (LPF):

Where

$$\varepsilon_1 = \sqrt{(10^{0.1Ap} - 1)}$$
$$\varepsilon_1 = \sqrt{(10^{0.1X3} - 1)}$$
$$\varepsilon_1 = \underline{\underline{1}}$$

$$\varepsilon_2 = \sqrt{(10^{0.1As} - 1)}$$
$$\varepsilon_2 = \sqrt{(10^{0.1X43} - 1)}$$
$$\varepsilon_2 = \underline{\underline{141.3}}$$

Calculate the number of orders:

$$n_B = \frac{\log(\varepsilon_2 / \varepsilon_1)}{\log(f_s / f_p)}$$

$$\eta_B = \frac{\log(\frac{141.3}{1})}{\log(\frac{45k}{25k})} = 8.27 \approx 9$$

So therefore choose $n_B = 9$ order

According to the calculation need to choose the 9th order, and then calculate the value of capacitors needs to for LPF design. A Butterworth coefficients table is used as a reference to calculate the value of capacitors and the stages also refer to the table which shown as table 1. The first design 9th order by using 2nd order + 2nd order + 2nd order + 3rd order.

Table 1. Butterworth Coefficient Table

Order, n	**C_1 / C or R/R_1**	**C_2 / C or R / R_2**	**C_3/C or R/R_3**
9	1.455	1.327	0.5170
	1.305	0.7661	
	2.000	0.5000	
	5.758	0.1736	

Appendix 2

The scaling factor, C is found in a choice of R = 100k Ω
C is scaling capacitance:

$$C = \frac{1}{2\pi f_P R}$$

$$C = \frac{1}{2\pi(25kHz)(100K\Omega)}$$

$$\underline{\underline{C = 63.662\,pF}}$$

The values of the capacitor for stage 1, 2, 3 and 4 can be obtained from table 1, as follows.

Stage 1: $C_1 = 5.758 \text{ x } 63.662 \text{ X } 10^{-12} = \underline{366.55 \text{ X } 10^{-12} \text{ F}}$
$C_2 = 0.1736 \text{ x } 63.662 \text{ X } 10^{-12} = \underline{11.05 \text{ X } 10^{-12} \text{ F}}$
Stage 2: $C_3 = 2 \text{ x } 63.662 \text{ X } 10^{-12} = \underline{127.32 \text{ X } 10^{12} \text{ F}}$
$C_4 = 0.5 \text{ x } 63.662 \text{ X } 10^{-12} = \underline{31.83 \text{ X } 10^{-12} \text{ F}}$
Stage 3: $C_5 = 1.305 \text{ x } 63.662 \text{ X } 10^{-12} = \underline{83.07 \text{ X } 10^{-12} \text{ F}}$
$C_6 = 0.7661 \text{ x } 63.662 \text{ X } 10^{-12} = \underline{48.77 \text{ X } 10^{-12} \text{ F}}$
And, stage 4
$C_8 = 1.455 \text{ x } 63.662 \text{ X } 10^{-12} = \underline{92.67\text{X } 10^{-12} \text{ F}}$
$C_7 = 1.327 \text{ x } 63.662 \text{ X } 10^{-12} = \underline{84.48 \text{ X } 10^{-12} \text{ F}}$
$C_9 = 0.517 \text{ x } 63.662 \text{ X } 10^{-12} = \underline{33.91 \text{ X } 10^{-12} \text{ F}}$

Appendix 3

For high-pass filter (HPF):
Where,

$$\varepsilon_1 = \sqrt{(10^{0.1Ap} - 1)}$$

$$\varepsilon_1 = \sqrt{(10^{0.1X3} - 1)}$$

$$\varepsilon_1 = \underline{\underline{1}}$$

$$\varepsilon_2 = \sqrt{(10^{0.1As} - 1)}$$

$$\varepsilon_2 = \sqrt{(10^{0.1X43} - 1)}$$

$$\varepsilon_2 = \underline{\underline{141.3}}$$

Calculate the number of orders:

$$n_B = \frac{\log(\mathcal{E}_2 / \mathcal{E}_1)}{\log(f_s / f_p)}$$

$$\eta_B = \frac{\log(\frac{141.3}{1})}{\log(\frac{1kHz}{2kHz})} = 7.14 \approx 8$$

So therefore $\eta_B = 8$ choose order

For HPF, need to calculate the value of the resistors and the capacitor value are fixed to 0.05uF to find the scaling resistor. By referring to the Butterworth coefficients table which shown as table 2 for 8th order.

Table 2 Butterworth Coefficients Tables

Order, n	**C_1 / C or R/R_1**	**C_2 / C or R / R_2**	**C_3/C or R/R_3**
	1.020	0.9809	
8	1.202	0.8313	
	1.800	0.5557	
	5.125	0.1950	

Choose C = 0.05μF,

Appendix 4

So the scaling factor R is:

$$R = \frac{1}{2\pi f_P C}$$

$$R = \frac{1}{2\pi(2kHz)(0.05uF)}$$

$$\underline{\underline{R = 1591.5\Omega}}$$

Stage 1: $R_2 = \frac{1591.5\Omega}{5.125} = \underline{310.5\Omega}$

$R_1 = \frac{1591.5\Omega}{0.1950} = \underline{8161.5\Omega}$

Stage 2: $R_3 = \frac{1591.5\Omega}{1.800} = \underline{884.2\Omega}$

$R_4 = \frac{1591.5\Omega}{0.5557} = \underline{2864.0\Omega}$

Stage 3: $R_5 = \frac{1591.5\Omega}{1.202} = \underline{1324.0\Omega}$

$R_6 = \frac{1591.5\Omega}{0.8313} = \underline{1914.5\Omega}$

Stage 4: $R_7 = \frac{1591.5\Omega}{1.020} = \underline{1560.3\Omega}$

$R_8 = \frac{1591.5\Omega}{0.9809} = \underline{1622.5\Omega}$