

## Butterworth BPF design and analysis with using lumped elements, transmission lines and combined factors for C band

### C bandı için toplu elemanlar, iletim hatları ve birleşik faktörler kullanılarak Butterworth BPF tasarımı ve analizi

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#### Abstract

In the field of electronics, technological advancements bring about alterations in electronic devices. With the fast-paced advancements in the era of communication, the frequency bands are becoming congested. One of the frequencies utilized by Wi-Fi-6, 6 GHz, has garnered its share of attention in these changes. This study proposes the design of a Butterworth Bandpass Filter that can be utilized in the IEEE C Band, employing both lumped elements and microstrip transmission lines. The methodology for determining the length and width of the transmission lines, as well as the considerations taken into account during their modification, is provided. A composite filter comprising of both elements and lines is also presented. The combined filter design is aimed at resolving issues arising from the increasing frequency. During the design process, an 8th-order lowpass filter is generated using the Butterworth normalized table, and a bandpass filter with a 200 MHz bandwidth and a 6 GHz center frequency is obtained through the use of a resonant circuit. The dimensions of the transmission lines are determined using theoretical formulas and verified through Matlab files and the MWO-AWR optimization tool. The voltage gain graphs generated demonstrate that the designs created on an FR4 substrate are suitable for use in the IEEE C Band for Wi-Fi-6.

**Keywords:** Resonant circuit, Distributed transmission line, Wi-Fi-6, FR4, MWO-AWR.

#### Öz

Teknolojik yenilikler elektronik cihazlarda değişiklikler getirmektedir. İletişim çağındaki hızlı gelişmeler frekans bantlarını doldurmaktadır. Wi-Fi-6'nın kullanıldığı frekanslardan biri olan 6 GHz de bu gelişmelerden payını almaktadır. Bu çalışmada, hem toplu elemanlar hem de mikroşerit iletim hatları kullanılarak IEEE C Bandında kullanılabilecek bir Butterworth bant geçiren filtre tasarlanmıştır. İletim hatlarının uzunluk ve genişliğinin nasıl bulunduğu ve ilgili değerler değiştirilirken hangi hususlara dikkat edildiğine değinilmiş ayrıca eleman ve hatlardan oluşan birleşik bir filtre de sunulmuştur. Kombine filtre tasarımı sayesinde artan frekansla ilgili sorunlar aşılmıştır. Tasarım sırasında Butterworth normalize tablosu kullanılarak 8. dereceden bir alçak geçiren filtre üretilmiş akabinde bir rezonans devresi kullanılarak 200 MHz bant genişliğinde ve 6 GHz merkez frekanslı bir bant geçiren filtre elde edilmiştir. İletim hattı boyutları; teorik formüller, ardından Matlab dosyaları ve son olarak MWO-AWR optimizasyon aracı ile elde edilmiştir. Üretilen voltaj kazancı grafikleri, FR4 alt tabanı üzerinde üretilen tasarımların Wi-Fi-6 için IEEE C bandında kullanıma uygun olduğunu göstermektedir.

**Anahtar kelimeler:** Rezonans devresi, Dağıtılmış iletim hattı, Wi-Fi-6, FR4, MWO-AWR.

## 1 Introduction

Electronics is leading the innovations in technology. Advances in electronics are making circuits smaller and data communication faster. In order to achieve this, practical filters are needed. Using a distributed parameter transmission line (TL) instead of using single element circuits saves both time and money. During the circuit design, first of all, Chebyshev, Butterworth, Bessel etc. should be chosen to continue with. While some offer a faster cut-off frequency, some offer a slow cut-off but a smooth bandpass characteristic. The number of resonant circuit equations also provides a fast cut-off frequency. The choice of active or passive filter is also important [1]-[5].

Using the Chebyshev method at S band frequency, a 5<sup>th</sup> order bandpass filter was made on Rogers RT/duroid 6002 substrate by Al-Amin and Chowdhury [6]. A MSc thesis was written by Sümer on software proposing a microwave filter design using Butterworth or Chebyshev [7]. Combining the simplified real frequency technique with the algebraic network decomposition

was presented for matching the microwave circuits by using mixed, lumped and distributed elements is another novel study [8]. Another work is about lumped-distributed networks to describe lossless two-ports with frequency approach technique [9].

A two-variable circuit modeling method was presented in PhD thesis by Şengül corresponded with mixed lumped and distributed elements [10]. A Matlab tool was created to get LC, scattered or microstrip circuit to have Butterworth filter by Uslu and Sevgi [11],[12].

Most of the filter designs are done by transforming the LPF to other filters. As a result, it is significant that high attenuation in stopband regions and low insertion loss in bandpass regions. Adequate bandwidth, sharp cut-off and low ripple in quantity and dB depending on the application [1],[2],[13],[14]. Nth order, cascaded filter may also be used according to the research [15].

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In this investigation, Butterworth type bandpass filters are designed utilizing lumped components, transmission line components, and combined components.

The disparities and advantages are then elucidated. Following the presentation of the material and methodology, calculations, design, and simulations are performed. The outcomes are presented and potential discussions are conveyed, ultimately leading to the conclusion of the article.

## 2 Materials and method

In this article, a Butterworth BPF is designed in a few ways. The center frequency is selected as the C band, 6 GHz, and the bandwidth is 200 MHz. The filter, which is planned as an 8th order, can be used in Wi-Fi 6 applications. MWO AWR Program and its tools like TXLINE are used for the design. Apart from these, WEB sites with ready-made programs such as Microstrip Line Calculator [16] and Microstrip Inductance Calculator [17] are used. Matlab takes its place as another important application used [12],[18].

Lossy FR-4 has  $\epsilon_r = 4.5$  and  $R_{ho} = 0.688$  is used for the design. In some designs,  $\epsilon_r = 4.4$  and  $R_{ho} = 1$  but still same results are achieved.

While the substrate height is 1600  $\mu\text{m}$ , the conductive material thickness is 35  $\mu\text{m}$ . Loss tangent of the FR-4 is 0.019. While working on the designs, 3 different ways are followed: only lumped elements, only transmission lines and the mixed design. The MLIN apparatus from Circuit Elements of the AWR Program is frequently used in the transmission lines phase.

First of all, it should be determined which technique will be used. Butterworth characteristic and Butterworth normalized lowpass filter component values ( $\omega_c = 1\text{rad/s}$ ,  $R_s = 1, 3\text{ dB}$  pass band ripple) in Table 1 are used in this study.

After the technique to be used is decided, the order is selected according to whether the cut-off frequency point is at sharp steepness.

In this study, the 8<sup>th</sup> order is used, except for the combined version. Next, it is selected whether to start with series inductance or parallel capacitance. In the circuit design, it is thought that the first element should be the series inductance. On the other hand, it is planned to start the transmission line circuit with a parallel line. The length and width values of the transmission line are sometimes found with the optimization

tool of the AWR Program or TXLINE plugin and sometimes with the equations. Now, let's find the LC values of our 8th-order circuit for low pass filter prototype with the help of center ( $f_0$ ), cut-off ( $f_c$ ) and desired bandwidth frequency for intended BPF ( $f_{BW}$ ) with these formulas [1]:

$$L_{2n-1} = \frac{Z_0 \times g_{2n-1}}{\omega_c} \quad (1)$$

$$C_{2n} = \frac{g_{2n}}{Z_0 \times \omega_c} \quad (2)$$

$$\omega_c = 2\pi \frac{f_{BW}}{2} = 2\pi f_c \quad (3)$$

$n$  starts from 1;  $Z_0$  is the characteristic impedance of transmission lines.

After gathering LC values; thanks to resonant circuits, a transition is made from low pass filter to band pass filter. In resonant circuits, series capacitance is added to series inductance and parallel inductance is added to parallel capacitance. In this time, let's find the LC values of our 8th order circuit for band pass filter with these formulas [1]:

$$L_{2n-1_{new}} = \frac{Z_0 \times g_{2n-1}}{2 \times \omega_c} = \frac{Z_0 \times g_{2n-1}}{\omega_{BW}} = \frac{L_{2n-1}}{2} \quad (4)$$

$$C_{2n-1} = \frac{1}{L_{2n-1_{new}} \times \omega_0^2} = \frac{\omega_{BW}}{Z_0 \times g_{2n-1} \times \omega_0^2} \quad (5)$$

$$C_{2n_{new}} = \frac{g_{2n}}{2 \times Z_0 \times \omega_c} = \frac{g_{2n}}{Z_0 \times \omega_{BW}} = \frac{C_{2n}}{2} \quad (6)$$

$$L_{2n} = \frac{1}{C_{2n_{new}} \times \omega_0^2} = \frac{Z_0 \times \omega_{BW}}{g_{2n} \times \omega_0^2} \quad (7)$$

Here, odd elements are connected series and even elements are parallel. Changing the  $g$  values can also switch between Butterworth, Chebyshev and Bessel. In addition,  $g$  selection can be made according to pass band ripple values. Theoretically, LC values for BPF are found with the formulas (4)-(7), but manufacturers do not produce inductance or capacitance at every value. In Table 2, the theoretical values and the values produced by the manufacturers, which are close to these values, are given.

Table 1. Butterworth normalized LPF component values.

N	$g_1$	$g_2$	$g_3$	$g_4$	$g_5$	$g_6$	$g_7$	$g_8$
1	2.000							
2	1.414	1.414						
3	1.000	2.000	1.000					
4	0.765	1.847	1.847	0.765				
5	0.618	1.618	2.000	1.618	0.618			
6	0.517	1.414	1.931	1.931	1.414	0.517		
7	0.445	1.246	1.801	2.000	1.801	1.246	0.445	
8	0.390	1.111	1.662	1.961	1.961	1.662	1.111	0.390

Table 2. LC values for BPF.

	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$	$L_8$
Theoretical (nH)	15.5334	0.0398	66.202	0.02254	78.105	0.0266	44.2277	0.1133
Manufactur-er (nH)	15.5	0.033	66.2	0.02	78	0.025	44.1	0.1
	$C_1$	$C_2$	$C_3$	$C_4$	$C_5$	$C$	$C_7$	$C_8$
Theoretical (pF)	0.04534	17.691	0.0106	31.242	0.009	26.4809	0.016	6.21337
Manufactur-er (pF)	0.05	17.8	SC	31.2	SC	26.4	SC	6.2

To find the length (L) and width (W) values for MLIN, the electrical length ( $\beta l$ ) value must first be found for each element. With the help of (8)-(10), the values required for the use of transmission line are found.

$$\beta l = \frac{LZ_0}{Z_{high}} \quad (8)$$

$$\beta l = \frac{CZ_{low}}{Z_0} \quad (9)$$

Here,  $Z_{high}$  is the maximum and  $Z_{low}$  is the minimum characteristic impedance that can be produced. It can be taken as  $120 \Omega$  and  $20 \Omega$ , respectively. Table 1 is used for L and C. The result is in radians. To convert to degrees, it is multiplied by 180 and divided by  $\pi$ . After obtaining the electrical length; the length and width of the transmission line are tried to be found by formulating [17] as well as programs such as the TXLINE Program or the online microstrip line calculator [16].

$$L_{\mu H} = 0.00508L \left[ \ln \frac{2L}{W+H} + 0.5 + 0.2235 \frac{W+H}{L} \right] \quad (10)$$

The  $L, W$  and  $H = 0.0629921$  values are in inch and  $L_{\mu H}$  is in microHenry in (10). For  $L$  and  $W$  lengths, previously written Matlab virtual tools are also looked at [12],[18].

Although specific  $L$  and  $W$  values for inductance and capacitance are found, these values are not so important because of the Optimization Tool in AWR Program. The old values will be changed with the Optimization Tool. However, in

order to optimize within an infinite number, it is necessary to enter a value close to the relevant value. The calculations made are to find the values required for optimization. Since the values will change with the optimization, the transmission line circuit started with parallel MLIN.

The MLIN lengths and widths obtained after the necessary optimization processes are given in Table 3. Values are in  $\mu m$ .

Table 3. MLIN L and W values for BPF.

	$TL_1$	$TL_2$	$TL_3$	$TL_4$	$TL_5$	$TL_6$	$TL_7$	$TL_8$
length (L)	850	100	364	136	164	371	258	131
width (W)	1	100	1	50	7	371	6	76
	$TL_9$	$TL_{10}$	$TL_{11}$	$TL_{12}$	$TL_{13}$	$TL_{14}$	$TL_{15}$	$TL_{16}$
length (L)	134	332	125	133	238	131	729	428
width (W)	7	100	4	07	9	6	219	100

After all, just the 2nd order, a different filter design has been made. The relevant filter is presented in 3 different ways: only lumped, only MLIN and combined. In Design and Simulation section, the circuits and the graphs are shown.

### 3 Design and simulation

The 8th order Butterworth BPF with theoretical lumped elements, possible realization theoretical lumped elements, lumped elements produced by the manufacturer and transmission lines are shown in Figure 1-4, respectively.

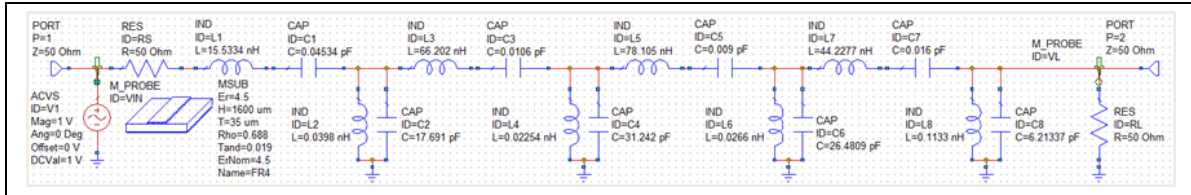


Figure 1. 8th order Butterworth BPF schematic with theoretical values of lumped elements.

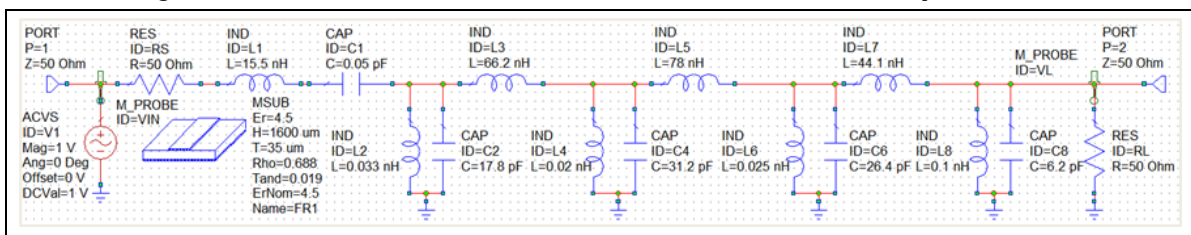


Figure 2. 8th order Butterworth BPF schematic with possible realization theoretical values of lumped elements.

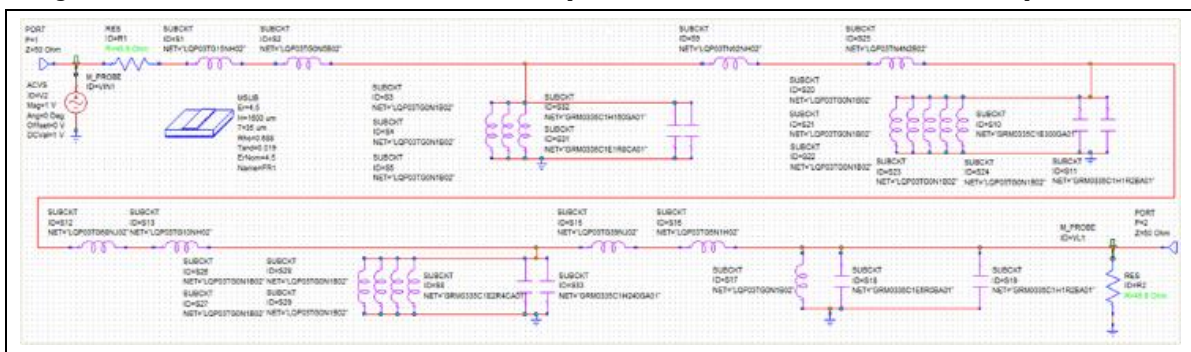


Figure 3. 8th order Butterworth BPF schematic with lumped elements produced by the manufacturer.

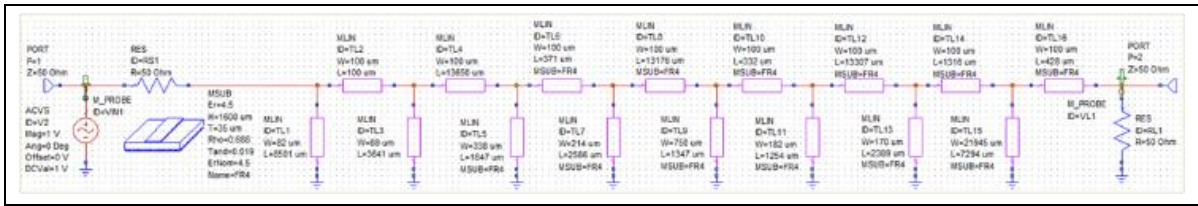


Figure 4. 8<sup>th</sup> order Butterworth BPF schematic with transmission lines.

In Figure 5, the voltage gain graph of the 8th order Butterworth BPF, which is created with theoretical values, is seen with ripples in the band pass region. Although the Butterworth application is decided in the filter selection, it is observed that there are ripples of around 0.7 dB. Insertion loss is around 9.5 dB and band width is 210 MHz. Center frequency is at 6 GHz. In Figure 6, the same graph is shown with 2 GHz to 10 GHz. Moreover, the gain value that will occur when the location of the input and output changes is also given.

In Figure 7, it is desired to give the voltage gain graph, which is the result of the theoretical real values and the real values produced by the factories. There are shifts in the center frequency in both. The gain value has decreased considerably. If it is to be continued with lumped elements, the operation must be restarted. On the other hand, in Figure 8, all designs graphs are given together and it is seen that the theoretical design and the design with the transmission lines (distributed) are close for center frequency and gain. Even the bandwidth is similar, albeit slightly increased for distributed design.

The variation of the voltage gain graph with the order change can be seen in Figure 9. Both 2<sup>nd</sup> and 8<sup>th</sup> order filters are supplied together which are created by distributed elements. 2<sup>nd</sup> order distributed design can be seen in Figure 10 with MTEEX and MCURVE.

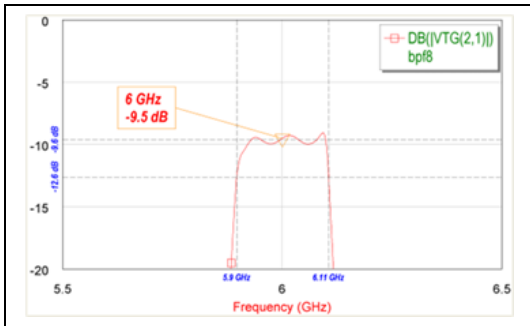


Figure 5. 8<sup>th</sup> order Butterworth BPF voltage gain graph and ripples with theoretical values.

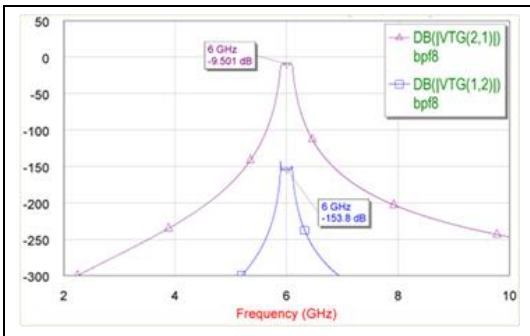


Figure 6. 8<sup>th</sup> order Butterworth BPF voltage gain graph with theoretical values, full view.

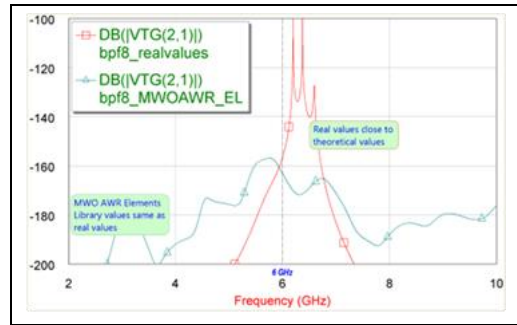


Figure 7. 8<sup>th</sup> order Butterworth BPF voltage gain graph with real and manufacturer (MWO AWR Elements Library) values.

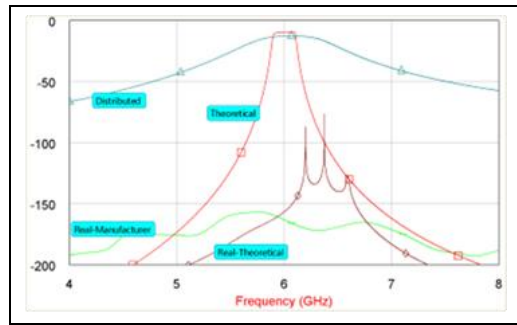


Figure 8. 8<sup>th</sup> order Butterworth BPF voltage gain graph with all designs.

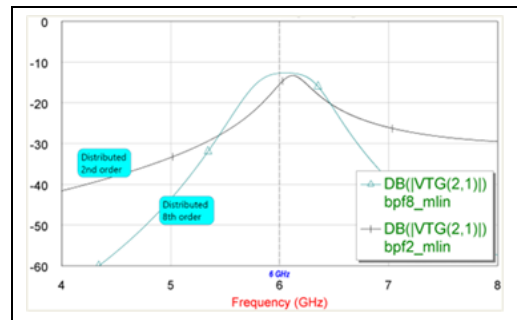


Figure 9. 2<sup>nd</sup> and 8<sup>th</sup> order Butterworth BPF voltage gain graph with transmission lines.

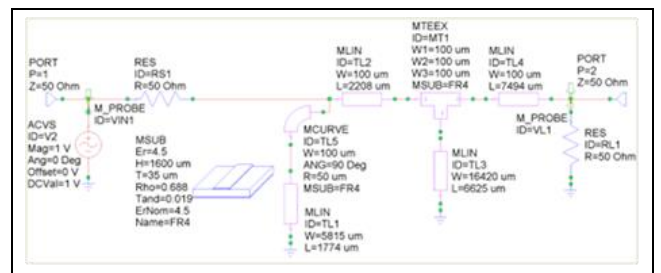


Figure 10. 2<sup>nd</sup> order Butterworth BPF schematic with transmission lines.

Figure 10 consisting fully of lumped elements, in Figure 11, and combined form, in Figure 12 are given, at last.

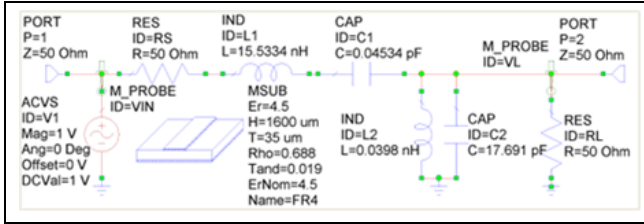


Figure 11. 2<sup>nd</sup> order Butterworth BPF schematic with lumped elements.

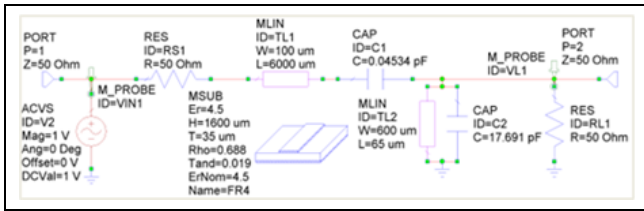


Figure 12. 2<sup>nd</sup> order combined Butterworth BPF schematic.

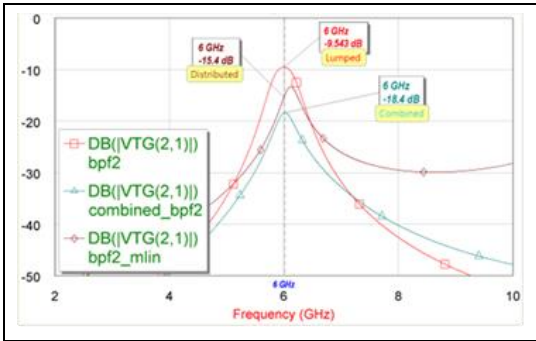


Figure 13. 2<sup>nd</sup> order Butterworth BPF voltage gain graph for all designs.

In Figure 13, voltage gain graphs for the circuits of Figure 10-12 are given together. Finally, theoretically, using another Matlab Program file [18], Figure 14 are produced. It is again a Butterworth BPF and it is absolutely similar to our theoretical design.

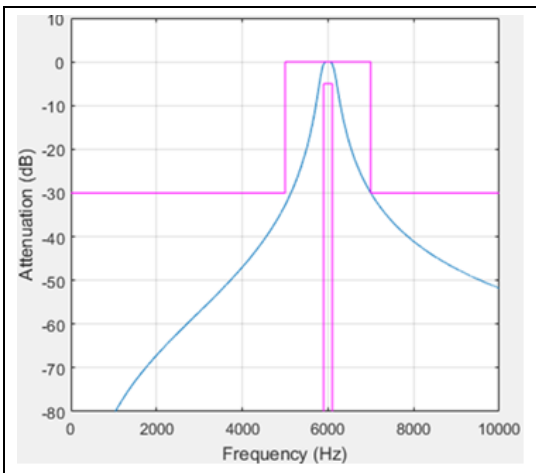


Figure 14. Digital Butterworth BPF graph.

## 4 Results and discussion

The production plan of the manufacturers has a significant impact on the circuits. If the circuit will be made with lumped

elements, the process should be done according to the materials that are or may be in the laboratory.

Even though the Butterworth topology is applied, there can be ripples like Chebyshev. Whether it has any side effects on the electronic circuit to which the filter will be installed should be well investigated.

With the increase in order, the band pass region is reached sharply. Stop band attenuation is come rapidly.

In the circuit made with distributed elements, stop band attenuation is not reached immediately, but it can be obtained as much as the circuit will work. By means of the combined filter design; problems with the increasing frequency, such as the difficulties in product supply, time losses, the trouble caused by the reduction of the area on the printed circuit board, the lack of manpower will be overcome.

## 5 Conclusion

A very successful BPF can be designed with the theoretically generated values on the computer program. Unfortunately, not all values can be produced by the manufacturers, so changes can be made during the implementation phase. This change can cause undesirable effects on the filter. Bandwidth may change, center frequency may shift, gain may decrease. Also, producing circuits with lumped elements can be costly and cumbersome. Right at this moment; distributed transmission lines help us to create circuits.

In this study, both 8<sup>th</sup> and 2<sup>nd</sup> order circuits are created in various ways, the differences are discussed. A BPF operating at center frequency, with a bandwidth of approximately with Butterworth characteristic is valid. The BPF can be used in IEEE C Band of course for the 6 GHz applications as Wi-Fi 6 or Wi-Fi 6E.

## 6 Author contribution statement

In the scope of this study, Mehmet DUMAN contributed creating the idea, designing, obtaining resources and materials, collecting data, performing analyzes, designing the schematic and gathering literature, examining the results and writing.

## 7 Ethics committee approval and conflict of interest statement

"There is no need to obtain permission from the ethics committee for the article prepared".

"There is no conflict of interest with any person/institution in the article prepared".

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