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OPTIMIZED EIGHTH-ORDER ACTIVE-R BANDPASS FILTER FOR UHF RFID SYSTEMS: DESIGN, SIMULATION, AND EXPERIMENTAL VALIDATION

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ABSTRACT

This paper presents a functioning bandpass filter required for the front-end of the UHF RFID receiver since all signals outside the ultra-high frequency (UHF) time-shifting signals backscattered by the transmitter should be filtered. Therefore, taking into cognisance the wide range of link frequencies that the UHF EPC for UHF RFID allows, it is necessary to develop a filter with tight bandwidth to receive the RFID signal. This study addresses the challenge of designing an efficient eighth-order bandpass filter using multiple feedback topology for UHF RFID applications, overcoming limitations of conventional filters in terms of bandwidth control, roll-off rate and gain performance. The EPC standard for UHF RFID permits the communication from the RFID tag to reader in a modulation frequency that ranges from 40 kHz to 640 kHz. The eighth order active R bandpass filter utilizing the multiple feedback was designed by using the multiSim simulation software version 11.1. Comparisons were made between the simulated and constructed filters, Performance metrics were evaluated based on gain, bandwidth, and roll-off rate, comparing simulated and constructed filters to theoretical expectations. Results obtained were compared using filter theory of maximum gain, bandwidth and roll-off rate. The experimental results show a maximum pass-band gain of 118.02 dB, 112.10 dB better than the 109.89dB and 106.50 dB, a roll-off rate of -64.93 dB/decade, 65.549 dB/decade better than the -73.226 dB/decade of the Simulated filter but a bandwidth of 25.10 kHz of the Simulated filter better than the 23.53kHz of the experimental filter, demonstrating improved performance over conventional designs.

Keywords: Multiple Feedback, Eighth-Order, Active-R Filter, bandpass, UHF RFID

INTRODUCTION

In the reader, the front-end system needs RC filter and Active Band pass filter and an Active low-pass filter to reject the undesired signal (Zin, and Zaw, 2009). Filters are essential components in the many electrical systems. In the state-of-the-art RF receivers, high performance filters are required to remove undesired signals at different stages of the receiving process, such as noise from incoming signals the antenna receives undesired signals at the image frequency, and harmonics after the mixing operation (Zin *et al.*, 2009). The UHF RFID system, Active filters are used because of the following advantages (Sridevi, 2001; Löwenborg, 1999; Carlos, 2009);

i. The transfer function with inductive characteristics can be achieved by particular circuit design, resistors can be used instead of inductors.
ii. The high input impendence and low output impendence of the operational amplifier means that the filter circuit is excellent in isolation characteristics and suitable for cascade.
iii. Active components provides amplification, therefore active filters have high gains.

The active filter without the capacitor is called and Active-R filter and has received much attention due to its potential advantages in terms of miniaturization, ease of design and high frequency performance [Srinivasan, (1992); Shinde, Patil, and Mirkute, (2003)]. Also Active-R filter offer substantially low sensitivity characteristics as compared to R-C structure (Soderstand and Mitra, 1971). Active-R filters give greater stop band attenuation and sharper roll-off at the edge of the pass band. Also in terms of functionality the Active-R filter is better than the Active-RC (Igwe, Amah, and Atsuwe, 2014).

In the paper, active band-pass filter is designed and simulated. An active band-pass filter is used for the RFID system to reject all signals outside the (40-640) kHz signals and to amplify the low antenna signal. The most common filter responses are the butterworth, chebysshew and Basel types. Among these responses, butterworth type is used to get a maximally-flat response. Also, it exhibits a nearly flat pass-band with no ripple. The roll-off is smooth and monotonic with a low-pass or high-pass roll-off of 20dB/dec for every pole (Zin *et al.*, 2009). Thus an Eight-order Butterworth band pass filter would have an attenuation rate of -160dB/dec and 160dB/dec.

Designing high-performance bandpass filters for UHF RFID applications poses significant challenges. One major issue is achieving a high-order filter response with sharp roll-offs, high selectivity, and low insertion loss while maintaining a compact circuit size and low power consumption. The specific challenge addressed in this study is the design of a high-order (eighth-order) active-R bandpass filter with a center frequency suitable for UHF RFID applications (e.g., 868 MHz or 915 MHz), while ensuring: High selectivity to minimize interference from adjacent channels and ensure reliable RFID tag detection; Low insertion loss to maximize the signal-to-noise ratio (SNR) and maintain a stable communication link between the RFID reader and tag ; Compact circuit size to facilitate integration into RFID readers or tags, where space is limited and Low power consumption to prolong battery life in battery-powered RFID devices.

Recent studies have investigated various filter topologies and design techniques for UHF RFID applications. However, these studies have limitations in terms of filter order, selectivity, or circuit complexity. This study aims to address these limitations by designing an eighth-order active-R bandpass filter using the multiple feedback topology, optimized for UHF RFID applications. The Multiple Feedback (MFB) topology was chosen for the eighth-order active-R bandpass filter due to its superior performance, moderate complexity, and real-world applicability. A comparison with other filter topologies highlights the advantages of the MFB topology:

MFB are High-order capable, High Selectivity, Low Insertion Loss, Low Sensitivity to components, Moderate Component Count, Moderate Circuit Complexity, Suitable for RFID Applications, Suitable for UHF Frequencies and Suitable for integration. While, the Sallen-Key Limited to 2nd/3rd order, Moderate Selectivity, Moderate Insertion Loss, High Sensitivity to Components, Low Component Count, Simple Circuit Complexity, Limited due to low order RFID Applications, Limited for UHF Frequencies due to low order, Limited due to simplicity. Furthermore, State-Variable has High-order capable, High Selectivity, Low Insertion loss, Moderate Sensitivity to components, High Component Count, Complex Circuit Complexity, Suitable for RFID Applications, and Suitable for UHF Frequencies and is Suitable for integration. More so, Ladder has High-order capable, High Selectivity, Low Insertion loss, Low Sensitivity to components, High Component Count, Complex Circuit Complexity, Suitable RFID Applications, Suitable for UHF Frequencies and is Suitable for integration (Kuchl, 2009).

The MFB topology offers a balance between performance, complexity, and real-world applicability, making it an ideal choice for the eighth-order active-R bandpass filter. Its high selectivity, low insertion loss, and moderate complexity make it suitable for UHF RFID applications. In contrast, the Sallen-Key topology is limited to low-order filters and may not provide sufficient selectivity for UHF RFID applications. State-Variable topology offers high performance but at the cost of high complexity and component count. Ladder topology provides high performance but may be too complex and difficult to integrate for UHF RFID applications. Therefore, the MFB topology is the most suitable choice for the eighth-order active-R bandpass filter, offering a balance between performance, complexity, and real-world applicability (Bingting and Ziping, 2018).

Previous studies have primarily focused on designing low-order (second- or third-order) bandpass filters (Atsuwe & Mom, 2022: Andrea et al. 2020: Ndichu et al. 2017: Bingting and Ziking, 2018: Beqal et al.2020a: Adul, 2014: Beqal et al.2020b). However, these filters often lack sufficient selectivity and insertion loss for UHF RFID applications. This study addresses this gap by designing an eighth-order active-R bandpass filter. Existing bandpass filters often suffer from inadequate selectivity, leading to interference from adjacent channels [3]. This work fills this gap by employing a multiple feedback topology, which provides high selectivity and sharp roll-offs.

Previous studies have mainly focused on designing bandpass filters for narrow frequency ranges (e.g., 868 MHz or 915 MHz) (Dalibor et al. 2017). This study extends the frequency range to cover the entire UHF RFID spectrum (860-960 MHz). Many existing bandpass filter designs are too complex or difficult to integrate into RFID readers or tags (Shengping et al. 2024: Lakshmi & Bhaskar, 2022). This work addresses this gap by using a moderate-complexity multiple feedback topology, which is suitable for integration into UHF RFID devices.

Several previous studies have only presented simulated results without experimental verification (Mulijkar, 2020). This study fills this gap by providing experimental results that validate the simulated performance of the proposed filter.

This study contributes to the existing literature by:

Designing an eighth-order active-R bandpass filter with high selectivity and low insertion loss, employing a multiple feedback topology to achieve sharp roll-offs and high selectivity. Extending the frequency range to cover the entire UHF RFID spectrum, using a moderate-complexity topology suitable for integration into UHF RFID devices. Providing experimental results that validate the simulated performance of the proposed filter. The second-order multiple feedback circuit is presented in Figure 1(Atsuwe, Igwue and Amah, 2017)

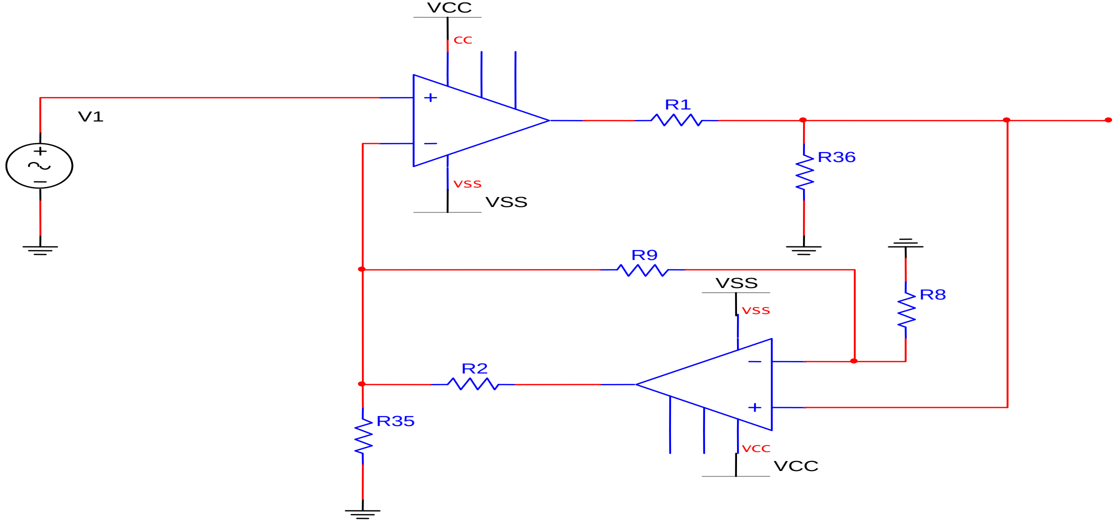


Figure 1: Second-Order Active-R Bandpass Filter using Multiple Feedback Topology

Kuchl, (2009) Butterworth filters have maximally flat pass-band response, which is a desirable trait for most analogue signal paths. A higher-order Butterworth filter further flattens the pass-band response and provides higher attention in the stop band. The second-order filter when used provides an amplitude roll-off rate of -40 dB/decade beyond the -3 dB cut off frequency. In general, the most common filter responses are the Butterworth and their advantages over others can be summarized as: Maximally flat response which exhibit nearly flat pass band with no ripple. The roll-off is smooth and monotonic with low-pass or high-pass roll-off of 20 dB/decades for every pole (Zin *et al.*, 2009; Reddy, 1976; Kureve *et al.*, 2014). This informed the choice of Butterworth filter response. Active filters with only resistors and operational amplifiers are Active-R filters. They are easy to design and have extension of response towards high frequencies (Shinde *et al.*, 2002; Soderstand, 1976). The operational amplifier shows the high frequency roll-off due to parasitic capacitance. Active-R circuits contain only op-amps and resistors so that they are suitable for high frequency operation and integration with the bipolar monolithic technology (Srinivasa, 1976 and Masami, 1992). The need for the above advantages of the Active-R filter made it suitable for use over the Active-RC filter whose conventional analog circuits use the ratio of resistance to set the transfer function of filter circuits. The values of RC (Resistor-capacitors) product determine the frequency responses of these circuits (Shinde *et al.*, 2002; Shinde *et al.*, 2008; Srinivasan, 1976; Ghausi, 1984). It is very difficult to make resistors and capacitors with the values and accuracy that are required in audio and instrumental applications (Shinde *et al.*, 2010). Stage 1 of figure 1 (the first op. amp A_1) shows the second-order Bandpass R-filter used in this work to design the Eighth-order band-pass R-filter configuration. The circuit was proposed by Prahbat *et al.* (2006).

The multiple feedback topology has already been successfully applied by the authors for the optimization of the design of an analog circuit for RFID (Atsuwe, Igwue and Amah, 2017). In this study, the Multiple Feedback topology method is utilized to design an eighth order active band-pass filter, for UHF RFID Implementation and the selection of the discrete components (capacitors and resistors) must be among industrial series to reach the defined specifications, this approach significantly reduces the design error when compared to the conventional method as the study (Atsuwe, Igwue and Amah, 2017) shows. In order to check the obtained results MULTISIM software was used for performing simulations.

MATERIALS AND METHODS

The materials used in the design and construction of the eighth-order active-R bandpass filter using MFB topologies are:

i. Sixteen (08) op.amps (A 6259)
ii. Sixty-four (24) Resistors (344.83Ω – 287KΩ)
iii. Connecting wires
iv. Soldering iron
v. Lead for joining wires.
vi. Circuit Boards (3).

Design of eighth-order active-r filter using mfb topology

The eighth-order active-R filter was designed through the cascading of four second order filter stages using MULTISIM version 11.0 software. Therefore the eighth-order filter designed using multiple feedback topologies is presented in Figure 2. (Atsuwe, Igwue and Amah, 2017)

The design considered the transfer function for the gain of the second order filter stage from equation 2. Amah *et al*. (2014) as

$$\frac{V_0}{V_i} = \frac{(S+GB_iK_2/Q)GB_iK_2}{S^2+\frac{SGB_iK_2}{Q+GB_i^2K_2^2}} \qquad (1)$$

Where V_o and V_i are output and input voltages respectively, and GB_i and K_2 are the gain bandwidth product of the op.amp and attenuator of the second op.amp.

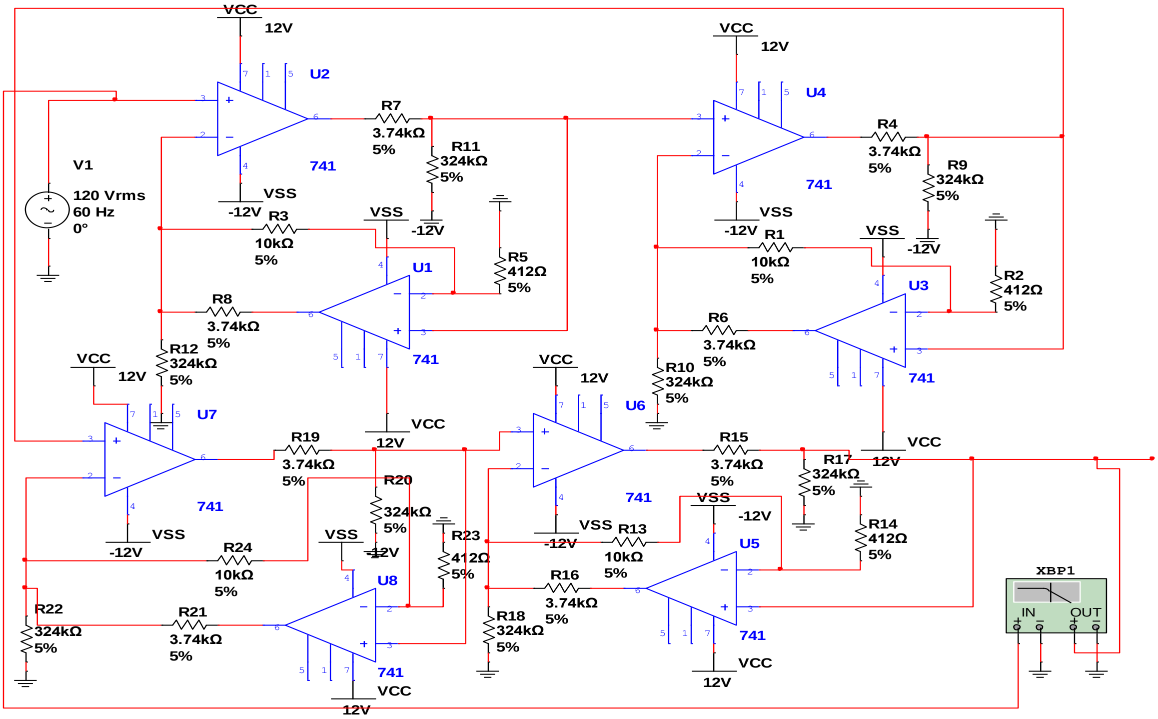


Figure 2: Multiple Feedback Eighth-Order Active-R Filter

The values of the different resistances are given as

$$R_4=\frac{K_1\times R_3}{(1-K_1)} \qquad (2)$$

$$R_2=\frac{K_2\times R_1}{(1-K_2)} \qquad (3)$$

Since K_1 and K_2 are attenuators, their values are given as

$$K_1 = \frac{1}{Q}= \frac{R_4}{R_3+R_4} \qquad (4)$$

$$K_2 = \frac{R_2}{R_1+R_2} = \frac{2\times\pi\times f}{\frac{A_o}{T}} \qquad (5)$$

$$R_3 = R_4(Q-1) \qquad (6)$$

The value of ${}^{A_o}/_{T}$ is taken as 6.2×10^6 which is the gain bandwidth product of the amplifier. The gain of the filter can be determined by using equation 1.Thus the role of attenuator

K_2 is that, it controls the open loop gain of operational amplifiers used in the circuit. Therefore the adjustment of K_2 results in control of centre frequency of the bandpass filter. The resistances R_2's can be varied using field effect transistor (FET) replaced resistances, thus giving single control of two attenuatorsK_2. The quality factor Q is independently adjusted using elementK_1, which is adjustable through resistance R_4.

The component values were calculated using equations 2, 3, 4, and 5. First, equation 5 was used to calculate the value of the attenuator K_2, then you find the value of R_2, but before that, we assume value of R_1 to insert into equation 3 to calculate the value of the resistor R_2. Again, resistor R_4 will be calculated using equation 2, but first, we shall use equation 4 to calculate the value of attenuator K_1 and then substitute into equation 2 to get the value of R_4.

Note that K_1 and K_2 are attenuators formed by voltage divider networks of resistors R_1, R_2, R_3, R_4, R_5 and R_6 where R_1=R_5 and R_2=R_6. Using equations 2-6, we calculated the resistor values as presented in tables 1 and 2.

Table 1: Resistor Values for Eight-order MFB Active-R Bandpass Filter Network at Q=25

S/N	FLF(MHz)	BLF(kHz)	Calculated Resistor Values				Experimental Resistor Values			
			R_1(kΩ)	R_2(kΩ)	R_3(kΩ)	R_4(Ω)	R_1(kΩ)	R_2(kΩ)	R_3(kΩ)	R_4(Ω)
1	860	40	97.60	2.50	10	416.67	97.60	5.10	10	412.00
2	880	107	97.60	7.03	10	416.67	97.60	21.50	10	412.00
3	900	160	97.60	10.91	10	416.67	97.60	47.50	10	412.00
4	910	256	97.60	18.71	10	416.67	97.60	220.00	10	412.00
5	920	320	97.60	24.53	10	416.67	63.40	250.00	10	412.00
6	930	465	97.60	40.27	10	416.67	29.40	274.00	10	412.00
7	940	640	97.60	65.74	10	416.67	13.00	287.00	10	412.00

Table 2: Resistor Values for Eight-order MFB Active-R Bandpass Filter Network at Q=30

S/N	FLF(MHz)	BLF(kHz)	Calculated Resistor Values				Experimental Resistor Values			
			R_1(kΩ)	R_2(kΩ)	R_3(kΩ)	R_4(Ω)	R_1(kΩ)	R_2(Ω)	R_3(kΩ)	R_4(Ω)
1	860	40	97.60	2.50	10	344.83	97.60	5.00	10	344.83
2	880	107	97.60	7.03	10	344.83	97.60	21.50	10	344.83
3	900	160	97.60	10.91	10	344.83	97.60	47.50	10	344.83
4	910	256	97.60	18.71	10	344.83	97.60	196.00	10	344.83
5	920	320	97.60	24.53	10	344.83	63.40	250.00	10	344.83
6	930	465	97.60	40.27	10	344.83	29.40	274.00	10	344.83
7	940	640	97.60	65.74	10	344.83	12.70	287.00	10	344.83

Implementation of the eighth-order active-R filter using mfb topology

The operational amplifiers (A6259) were first mounted on the circuit workbench with two op. amps. used for the first stage, another two for the second stage, the next two for the third stage and the last two for the fourth stage. This makes the filter an eighth-order (four stages) filter. The A6259 op-amps were chosen for their exceptional performance characteristics, including high GBW, low noise, high slew rate, and low power consumption. These features make them well-suited for high-frequency applications like UHF RFID, and their availability and cost make them a practical choice for the eighth-order active-R bandpass filter. Resistors were then coupled accordingly using wires. More so, oscilloscope and signal generators from the software workbench were mounted on the circuit and connected appropriately. The circuit performance was studied with different values of Q (Q = 25 and 30) with variable centre frequencies f_0 (f_0 = 40 kHz, 107 kHz, 160 kHz, 256 kHz, 320 kHz, 465 kHz, 640 kHz). The Tables 1 and 2 on appendix A, show resistor values at centre frequencies of Q = 25 and Q = 30, for the active R-band pass filter using multiple feedback topology.

Here is a schematic illustrating the component arrangement for the eighth-order active-R bandpass filter:

This schematic illustrates the component arrangement for the eighth-order active-R bandpass filter, including:

Here are some numerical examples explaining how resistor and attenuator values were derived:

A6259 Op-Amp, Resistors (R_1, R_2, R_3, R_4, R_5, R_6) to calculate the resistor values, we specifically use equations 2 t0 6 above.

Therefore for Q=25

R_1 = 97.60 kΩ; R_2 = 2.50 kΩ, 7.03 kΩ, 10.91 kΩ, 18.71 kΩ, 24.53 kΩ, 40.27 kΩ, 65.74 kΩ

R_3 = 10 kΩ; R_4= 416.67 Ω

Note that the component values may need to be adjusted based on the specific requirements of the filter.

After calculating the values, the experimental or preferred values suitable for constructing the filter were chosen as follows for Q=25;

R_1 = 97.60 kΩ, 63.40 kΩ, 29.40 kΩ, 13.00 kΩ

R_2 = 5.00 kΩ, 21.50 kΩ, 47.50 kΩ, 220.00 kΩ, 250.00 kΩ, 274.00 kΩ, 287.00 kΩ

R_3 = 10 kΩ; R4= 421.00 Ω,

The values are then calculated using the same process enumerated above using Q=30;

R_1 = 97.60 kΩ; R_2 = 5.00 kΩ, 47.50 kΩ, 196 kΩ, 250.00 kΩ, 274.00 kΩ, 287.00 kΩ,

R_3 = 10 kΩ; R_4= 344.83 Ω

The attenuator values were derived using the following equations:

K$_1$ = $\frac{1}{Q} = \frac{R_4}{R_3+R_4} = \frac{1}{25}$ =0.04 for Q=25 and 0.03 for Q=30

K$_2$ = $\frac{R_2}{R_1+R_2} = \frac{2\times\pi\times f}{\frac{A_o}{T}}$

An attenuation of 0.03 corresponds to a reduction in signal amplitude by approximately 3%, while an attenuation of 0.04 corresponds to a reduction in signal amplitude by approximately 4%.

The results show that a 1% resistor tolerance will result in a center frequency stability of approximately ±2% and a bandwidth stability of approximately ±2%. On the other hand, a 5% resistor tolerance will result in a center frequency stability of approximately ±10% and a bandwidth stability of approximately ±10%. Therefore, using 1% resistors instead of 5% resistors will improve the stability of the filter's center frequency and bandwidth. However, the cost of 1% resistors is typically higher than that of 5% resistors, so the choice of resistor tolerance will depend on the specific requirements of the application.

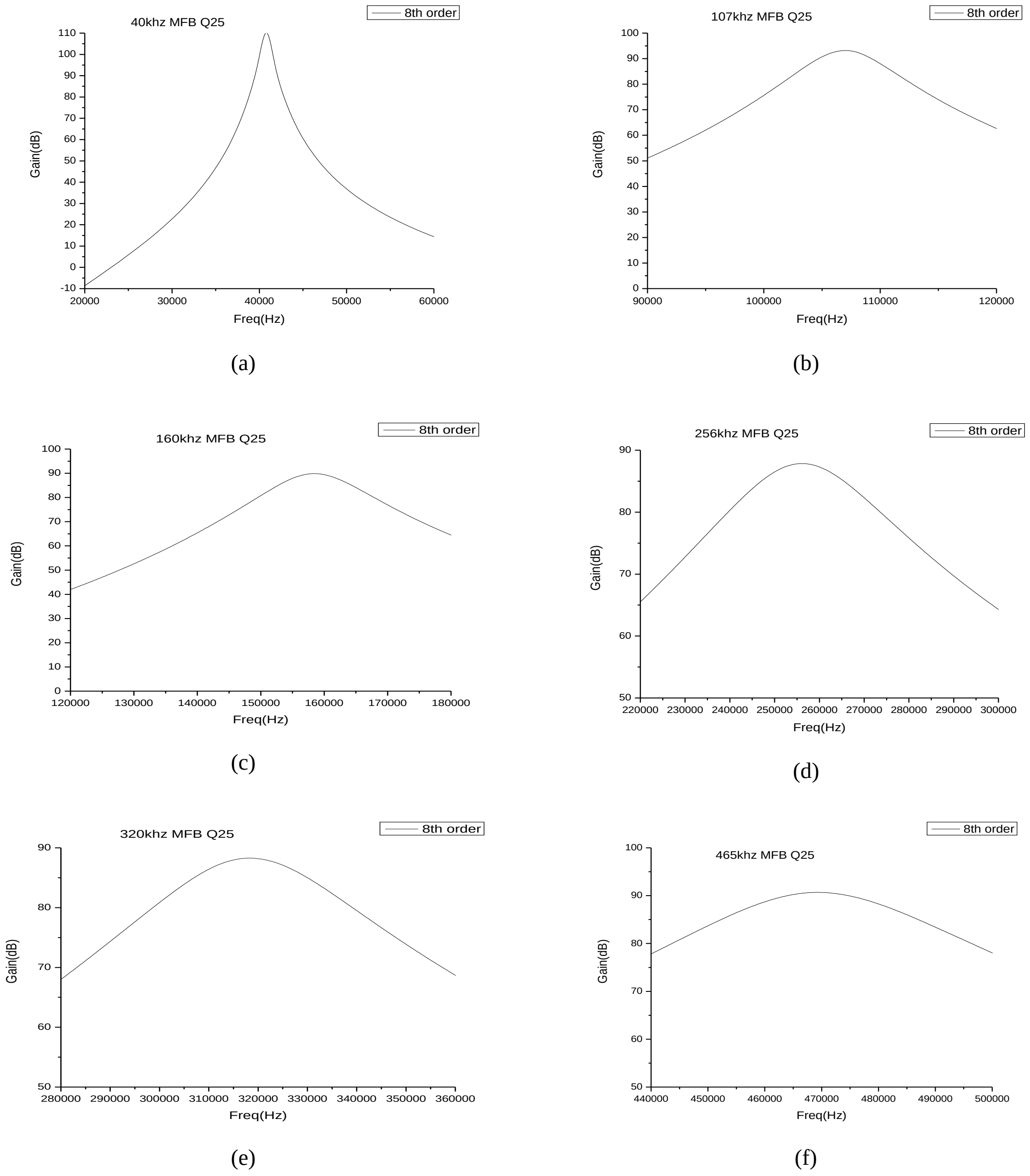
RESULTS AND DISCUSSION

Simulated (theoretical) Result for Eighth-Order Active-R Bandpass Filter using MFB Topology at Q = 25 and Q=30 at varying Centre Frequencies

The results obtained for the theoretical values of the eighth-order active-R bandpass filter using MFB topology at quality factors of Q=25 and Q=30 at varying centre frequencies from the resistor values in Tables 1 and 2 are presented in Figures 3(a)-(g) and 4(a)-(g).

Simulated (theoretical) results for eighth-order active-R bandpass filter using MFB topology at Q = 25 at varying centre frequencies

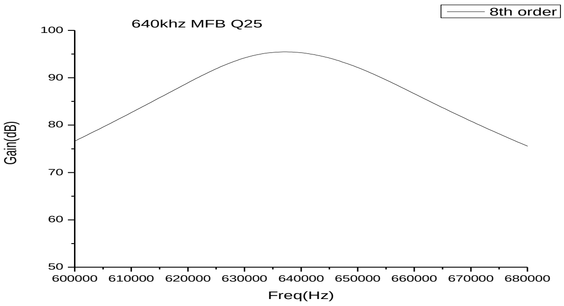
The results obtained from the simulated (theoretical) resistor values of the eighth – order active-R bandpass filter using MFB topology at constant quality factor of Q = 25 and varying centre frequencies in Table 1 is presented in Figures 3(a)-(g) below.



(a) (b)

(c) (d)

(e) (f)



(g)

Figure 3: Eighth-Order Active-R Bandpass Filter using MFB Topology at (a). F_0=40 kHz, (b). F_0=107 kHz, (c). F_0=160 kHz, (d). F_0=256 kHz, (e). F_0=320 kHz, (f). F_0=465 kHz, (g). F_0=640 kHz and Q=25

Simulated filter for MFB topology at Q=25 at varying centre frequencies (F_0)

From (Figures 8 to 14) the simulated results, the mid band gain, -3dB gain, higher cut-off frequency (F_H), lower cut-off frequency (F_L), bandwidth (BW) and Roll-off values obtained at different centre frequencies are shown in Table 3. From Table 3, the filter has a maximum pass band gain of 109.89dB at a centre frequency of 40 kHz and decreased inversely with centre frequency until it gets to 320 kHz from where it assumed direct proportionality. The minimum band gain is 87.766 dB at 256 kHz centre frequency. The Bandwidth increases with centre frequency when the bandwidth dropped from 24.309 kHz to 23.456 kHz. The minimum bandwidth is 0.853 kHz. The roll off rate also increases with centre frequency and peaks at frequency of 256 kHz before decreasing progressively to – 66.851 dB/dec. From Figure 3 we observed slight shift in centre frequency up to 40.809 kHz.

Table 3: Maximum Gain and Bandwidth of Eighth-Order Active-R Bandpass Filter using MFB Topology at variable Center Frequency and Constant Quality Factor of Q = 25 (Multisim)

F_0(kHz)	Mid Band Gain (dB)	-3dB Gain (dB)	F_H (kHz)	F_L (kHz)	BW (kHz)	Roll-off (dB/decade)
40	109.891	106.891	41.235	40.382	0.853	-73.226
107	93.282	90.282	109.111	104.713	4.398	-63.287
160	89.569	86.569	163.109	153.940	9.169	-56.191
256	87.766	84.766	266.060	246.442	19.618	-48.087
320	88.329	85.329	329.116	307.579	21.537	-50.846
465	90.617	87.617	481.715	457.406	24.309	-58.296
640	95.329	92.325	694.542	626.086	23.456	-66.851

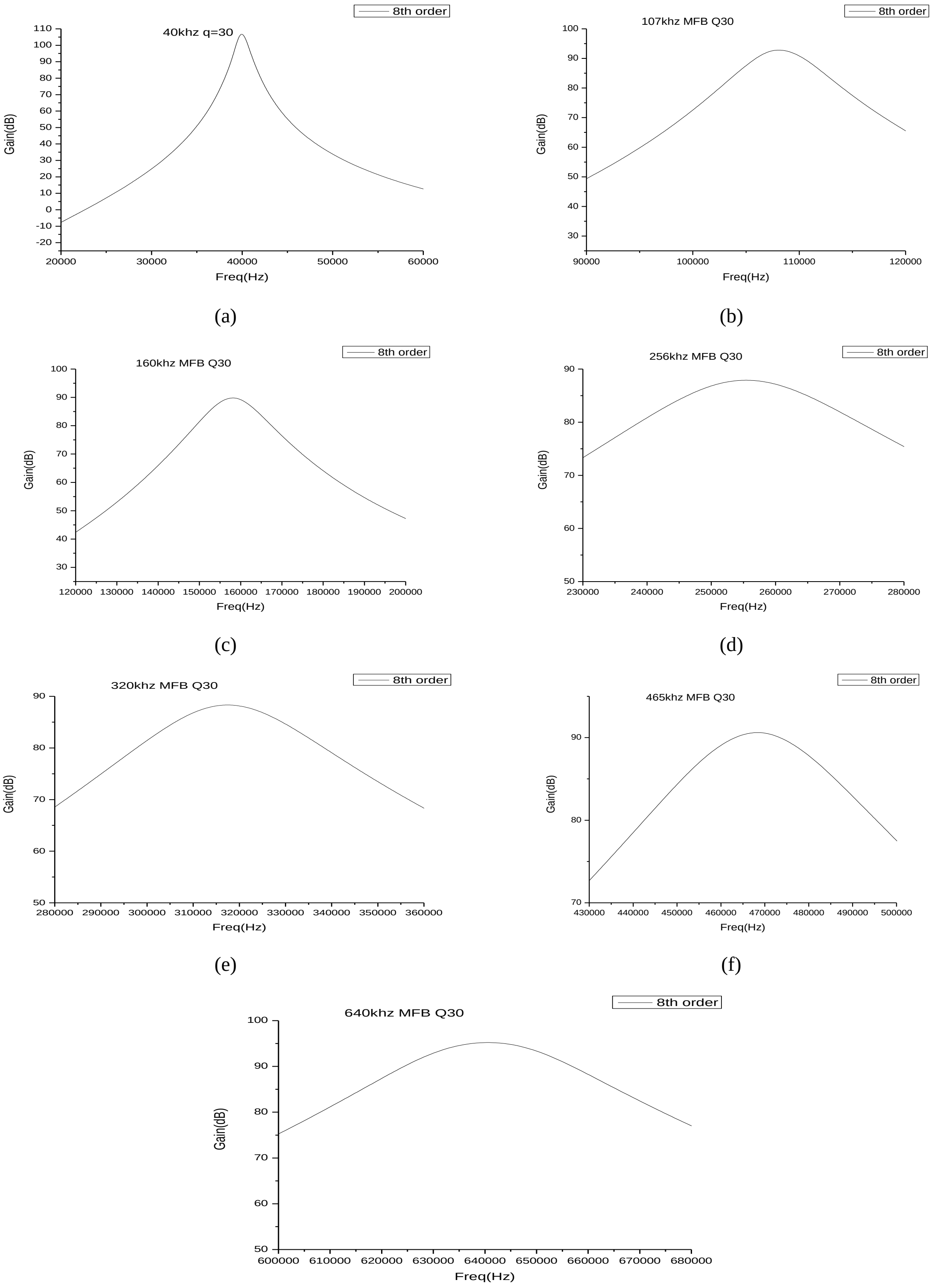
Table 4: Maximum Gain and Bandwidth of Eighth-Order Active-R Bandpass Filter using MFB Topology at variable Center Frequency and Constant Quality Factor of Q = 30 (Multisim)

F_0(kHz)	Mid Band Gain (dB)	-3dB Gain (dB)	F_H (Hz)	F_L (Hz)	BW (kHz)	Roll-off (dB)
40	106.505	103.505	40.453	39.494	0.959	-73.953
107	92.627	89.627	101.618	105.740	4.878	-193.000
160	89.896	86.896	162.506	153.763	8.743	-56.191
256	87.908	84.908	265.495k	245.771k	19.724	-48.087
320	88.449	85.449	328.512k	306.975k	21.537	-50.846
465	90.497	87.497	481.373k	455.997k	25.376	-58.296
640	95.085	93.085	653.416k	628.254k	25.162	-66.868

The behavior of the filter at this quality factor in terms of mid band gain can therefore be said to perform to specification up to a centre frequency (F_o) of 256 kHz and then deviates until it approaches F_o= 640 kHz. From filter theory, "The Mid Band Gain (G_{max}) decreases as the centre frequency increases" (Adnan *et al*., 2014: Ndichu et al., 2017). We can attribute the deviation to parasitic effect. Also, the bandwidth of the filter can be said to conform to filter theory despite the minor deviation at F_o= 640 kHz. Filter theory also stipulates that ''when centre frequency of a filter increases, it causes an increase in bandwidth" (Shinde, *et al*., 2002; Adnan *et al*., 2013; Chavan *et al*., 2013; Shinde *et al*., 2013; Shinde and Nuladkar, 2010; Shinde *et al*., 2003). The roll-off rate behaves like a third –order filter from the values obtained, but a single pole filter roll off gives 20xn dB/dec, where n is the filter order, the eighth- order should give 160 dB/dec (Jacob, 2003: Attri, 2005). The centre frequencies of the filter at this quality factor are slightly shifted by ± 0.02% to ± 2.0% of the actual centre frequency, but still within the specification of the epc global class I generation 2 protocol of ± 22 % for UHF RFID systems. Therefore the filter can be used in the reader of ultra high frequency radio frequency identification systems.

Simulated (theoretical) results for eighth-order active-R bandpass filter using MFB topology at Q = 30 at varying centre frequencies

The results obtained from the simulated (theoretical) resistor values of the eighth – order active-R bandpass filter using MFB topology at constant quality factor of Q = 30 and varying centre frequencies in Table 4 is presented in Figures 4(a)-(g).



(a) (b) (c) (d) (e) (f) (g)

Figure 4: Eighth-Order Active-R Bandpass Filter using MFB Topology at (a). F_0=40 kHz, (b). F_0=107 kHz, (c). F_0=160 kHz, (d). F_0=256 kHz, (e). F_0=320 kHz, (f). F_0=465 kHz, (g). F_0=640 kHz and Q=30

Simulated filter for MFB topology at Q=30 at varying centre frequencies (F_0)

From Figure 4(a)-(g), the simulated results, the mid band gain, -3dB gain, higher cut-off frequency (F_H), lower cut-off frequency (F_L) bandwidth (BW) and Roll-off values obtained at different centre frequencies are shown in Table 4. From Table 4 above, the filter has a maximum pass band gain of 106.505 dB at a centre frequency of 40 kHz and decreased inversely with centre frequency until it gets to 320 kHz from where it assumed direct proportionality. The minimum band gain is 87.908 dB at 256 kHz centre frequency. The Bandwidth increases with centre frequency except at centre frequency of 640 kHz when the bandwidth dropped from 25.376 kHz to 25.162 kHz. The minimum bandwidth is 0.959 kHz. The roll off rate also increases with centre frequency and peaks at frequency of 256 kHz before decreasing progressively to – 66.868 dB/dec. From Figure 15 to 21 we observed a slight shift in centre frequency of 40.027 kHz at F_o= 40 kHz to 640.622 kHz at F_o= 640 kHz.

It was observed that the mid band gain performes to specification until it reaches the centre frequency (Fo) of 256 kHz and then deviates until it approaches Fo=640 kHz. From the filter theory, 'The mid band gain decreases as the centre frequency increases'. This is attributed to the parasitic effect. Despite the minor deviation at Fo= 640 kHz, the bandwidth of the filter is said to conform to the filter theory. The roll-off rate behaves like a third –order filter from the values obtained, but a single pole filter roll off gives 20xn dB/dec, where n is the filter order, the eighth- order should give 160 dB/dec (Jacob, 2003: Attri, 2005). The centre frequencies of the filter at this quality factor are slightly shifted from 0.07% at F_o= 40 kHz to 0.1% at F_o= 640 kHz, but still within the specification of the epc global class I generation 2 protocol of ± 22 % for UHF RFID systems. Therefore the filter can be used in the reader of ultra high frequency radio frequency identification systems. All the deviations noticed with this filter can be attributed to the high sensitivity of MFB topology to resistor values that cause parasitic effect to the filter.

Construction of the eighth- order active-R bandpass filter using MFB topology

The Construction (Experimental) of the Eighth - order Active - R Band pass filter using MFB and topology was done using 16 op. amps, 3 circuit boards and connecting wires. The Filter was constructed with a 5V power supply, a signal generator and an oscilloscope to determine its performance. The input from signal generator was adjusted to 5V peak-to-peak at a frequency of 40 kHz for a start. The signal frequency was then varied in steps up to 640 kHz and the corresponding output voltage amplitude displayed on the oscilloscope was measured accordingly. The input voltage was kept at 5V throughout the experimental procedure. The filter bandwidth was determined by measuring F_H and F_L when the peak-to-peak output voltage was 0.707 times the value at the centre frequency. The roll-off was determined at -3dB point where the frequency is traced to the vertical axis (Gain).

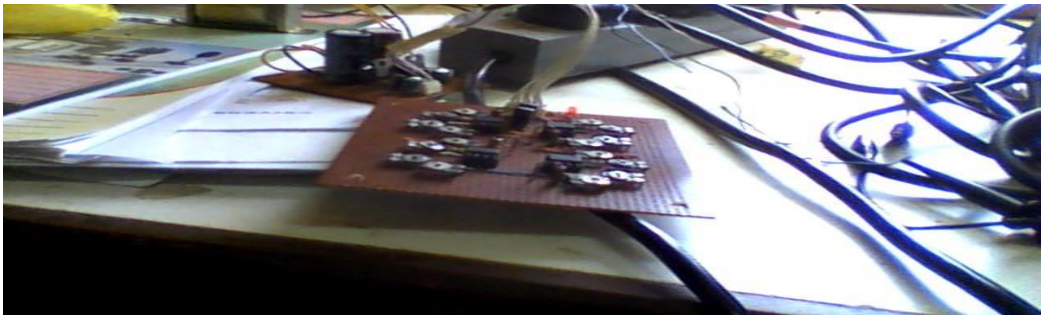


Plate 1: Constructed Eighth-Order Active-R Bandpass Filter using MFB Topology

Plate 2: Experimental Set-Up using Signal Generator and Oscilloscope for MFB

Experimental filter for eighth-order active-R bandpass filter using MFB topology at Q=25 at varying centre frequencies (F_o)

From the constructed filter shown on plate 1 and the experimental set-up shown on plate 2, the mid band gain, -3dB gain, higher cut-off frequency (F_H), lower cut-off frequency (F_L) bandwidth (BW) and Roll-off values obtained at different centre frequencies. The results of the centre frequency F_o, mid band gain dB, upper frequency F_H, lower frequency F_L and the roll-off rate ROR are shown in Tables 5 and 6 respectively.

Table 5: Maximum Gain and Bandwidth of Eighth-Order Active-R Bandpass Filter using MFB Topology at variable Centre Frequency and Constant Quality Factor of Q = 25 (EXPERIMENTAL)

F_0(kHz)	Mid Band Gain (dB)	-3dB Gain (dB)	F_H (kHz)	F_L (kHz)	BW (kHz)	Roll-off (dB/decade)
40	118.020	115.020	40.940	40.729	0.211	-64.932
107	94.590	91.590	108.665	105.107	3.558	-62.345
160	90.670	87.670	162.481	154.543	7.940	-60.664
256	88.210	85.210	265.250	247.240	18.014	-59.781
320	88.740	85.740	328.533	308.194	20.340	-67.367
465	91.700	88.700	480.030	459.102	20.930	-58.296
640	96.830	93.830	648.301	627.670	20.632	-63.580

Table 6: Maximum Gain and Bandwidth of Eighth-Order Active-R Bandpass Filter using MFB Topology at variable Centre Frequency and Constant Quality Factor of Q = 30 (EXPERIMENTAL)

F_0(kHz)	Mid Band Gain (dB)	-3dB Gain (dB)	F_H (kHz)	F_L (kHz)	BW (kHz)	Roll-off (dB/ decade)
40	112.100	109.100	40.105	39.762	0.343	-65.549
107	93.860	90.860	110.330	106.231	4.100	-89.779
160	90.510	87.510	162.100	154.100	8.000	-60.361
256	88.140	85.140	264.880	246.140	18.740	-58.112
320	88.840	85.840	327.640	307.540	20.100	-61.454
465	91.580	88.580	478.980	457.540	21.440	-59.489
640	95.880	92.880	652.180	628.650	23.530	-67.264

The results presented in Table 5 shows obtained values for the Constructed Active- R Bandpass filter using multiple Feedback topology at constant quality factor Q = 25. We observed that the highest pass band Gain (G_{max}) was recorded at F_o= 40kHz with a value of 118.02dB while the least value of gain was recorded at F_o=256kHz with a value of 88.21dB. From Table 5, the filter has a maximum pass band gain of 118.020 dB at centre frequency of 40 kHz and decreased inversely with centre frequency until it gets to 320 kHz from where it assumed direct proportionality. The minimum band gain is -88.210 dB at 256 kHz centre frequency. The bandwidth increases with centre frequency except at centre frequency of 640 kHz when the bandwidth dropped from 20.930 kHz to 20.632 kHz. The minimum bandwidth is 0.211 kHz. The roll off rate also increases with centre frequency and peaks at frequency of 256 kHz before decreasing progressively to -66.851 dB/dec. Also from the table, we observed a slight shift in centre frequency from 40.835 Hz at F_o= 40 kHz to 632,459 Hz at F_o= 640 kHz. The behavior of the filter at this quality factor in terms of mid band gain can therefore be said to perfom to specification up to a centre frequency (F_o) of 256 kHz but deviates at centre frequency of 320 kHz to 640 kHz. From filter theory, "The Mid Band Gain (G_{max}) decreases as the centre frequency increases". We can attribute the deviation to parasitic effect. Also, the bandwidths of the filter conform to filter theory but with deviation at centre frequency of 640 kHz. Filter theory also stipulates that ''when centre frequency of a filter increases, it causes an increase in bandwidth".

The roll-off rate behaves like a third –order filter from the values obtained whereas it should have behaved like an eighth-order filter. Because a single pole filter roll off gives 20xn dB/dec, where n is the filter order, the eighth- order should give 160 dB/dec. The centre frequencies of the filter at this quality factor are slightly shifted from ± 2.0% at F_o= 40 kHz to ± 1.18% at F_o= 640 kHz, but this is still within the specification of the epc global class I generation 2 protocol of ± 22 % for UHF RFID systems. Therefore the filter can be used in the reader of ultra high frequency radio frequency identification systems. All the deviations noticed with this filter can be attributed to the high sensitivity of MFB topology to resistor values that cause parasitic effect to the filter.

Experimental filter for eighth-order active-R bandpass filter using MFB topology at Q=30 at varying centre frequencies (F_o)

From the constructed filter, the mid band gain, -3dB gain, higher cut-off frequency (F_H), lower cut-off frequency (F_L) bandwidth (BW) and Roll-off values obtained at different centre frequencies are shown in Table 6. The results presented in Table 6 show obtained values for the Constructed active- R bandpass filter using multiple Feedback topology at constant quality factor Q = 30. Also from Table 6, the filter has a maximum pass band gain of 112.100 dB at centre frequency of 40 kHz and decreased inversely with centre frequency until it gets to 320 kHz from where it assumed direct proportionality. The minimum band gain is 88.140 dB at 256 kHz centre frequency. The bandwidth increases with centre frequency and peaks at centre frequency of 640 kHz. The minimum bandwidth is 0.340 kHz. The roll off rate also increases with centre frequency and peaks at frequency of 256 kHz before decreasing progressively to -67.264 dB/dec. From Figure 36, we observed a slight shift in centre frequency 39,933 Hz at F_o= 40 kHz to 647,143 Hz at F_o= 640 kHz.

There is a deviation of the mid band gain at a centre frequency of 320 kHz after initial performance to specification of up to a centre frequency (F_o) of 256 kHz. The bandwidths of the filter conform to filter theory without deviation at any centre frequency. The roll-off rate behaves like a third –order filter from the values obtained whereas it should have behaved like an eighth-order filter. Because a single pole filter roll off gives 20xn dB/dec, where n is the filter order, the eighth- order should give 160 dB/dec (Jacob, 2003: Attri, 2005). The centre frequencies of the filter at this quality factor are slightly shifted, but still within the specification of the epc global class I generation 2 protocol of ± 22 % for UHF RFID systems. Therefore the filter can be used in the reader of ultra high frequency radio frequency identification systems (Beqal et al, 2020). All the deviations noticed with this filter can be attributed to the high sensitivity of MFB topology to resistor values that cause parasitic effect to the filter.

Comparison of results based on theoretical and experimental values for MFB topology at quality factors Q=25, Q=30 and varying centre frequency

The results of maximum band pass gain, bandwidth and roll-off rate presented in Tables 3 and 4 for the eighth-order active – R bandpass filter using multiple feedback topology from the simulated (theoretical) values were compared with results in Tables 5 and 6 obtained from the experimental or constructed values and the following results discussed.

Maximum pass band gain

Results obtained in Table 3 for the theoretical results was compared with the results in Table 5 for the experimental result of the eighth –order active – R bandpass filter using MFB topology at varying centre frequencies F_o and constant quality factor of Q = 25 using filter characteristics of Maximum Pass band Gain. The plot is shown in Figure 5. Figure 5 shows plot for the comparison of the maximum pass band gain (G_{max}) for eighth order active –R bandpass filter using MFB topology at a quality factor of Q=25 and varying centre frequency using theoretical and experimental values. The plot shows that the theoretical value for the maximum pass band gain (G_{max}) has trend that decreased from 109.89 dB at F_o= 40 kHz to 95.325 dB at F_o= 640 kHz compared to the experimental values for the maximum pass band gain (G_{max}) that also decreased from 118.02 dB for F_o= 40 kHz to 96.83 dB for F_o= 640 kHz. Though both theoretical and experimental values show decreasing trend of the mid band gain with the centre frequency (as indicated by the negative slope on the trend equations), the mid band gains are higher for the MFB experimental values compared to the theoretical values. This shows that in terms of the mid band gain, the experimental filter performed better than the theoretical. It also confirms the theory that MFB is characterized by high gain.

More so, results obtained and presented in Table 4 for the theoretical results was compared with the results presented in Table 6 for the experimental result of the eighth –order active – R bandpass filter using MFB topology at varying centre frequencies F_o and constant quality factor of Q = 30 using filter characteristics of maximum pass band gain. The plot is shown in Figure 6. Figure 6 above, shows plot for the comparison of maximum pass band gain (G_{max}) for the eighth order active- R bandpass filter using MFB topology at a quality factor of Q = 30 and varying centre frequencies using theoretical and experimental values, the plot show that the theoretical values of the maximum pass band gain (G_{max}) decreased from 106.505 dB at F_o= 40 kHz to 95.085 dB at F_o= 640 kHz compared to the experimental values that also decreased from 112.10 dB at F_o= 40 kHz to 95.88 dB at F_o= 640 kHz. The trends show that both the theoretical and the experimental values are decreasing with increasing centre frequency as validated by the negative slope in the trend equation. This also show that the experimental values are higher than the theoretical values making it better in terms of maximum pass band gain.

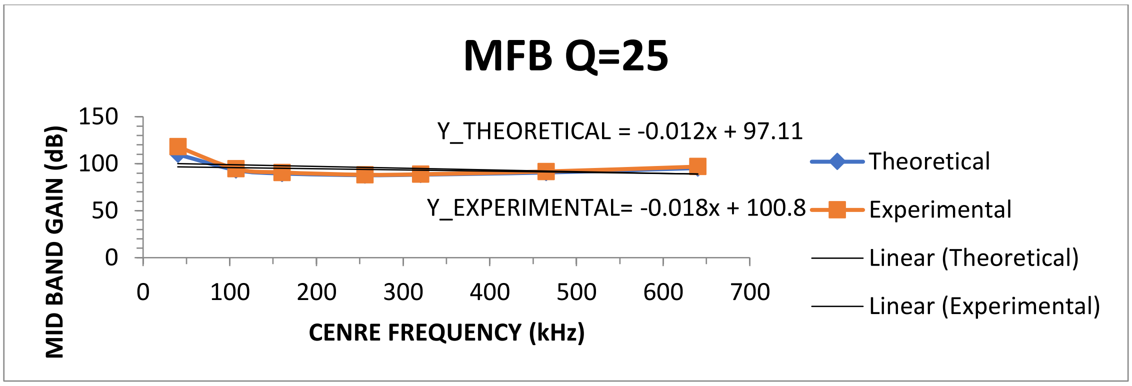


Figure 5: Comparison of Theoretical and Experimental Maximum Pass band Gain for MFB Topology at Q=25

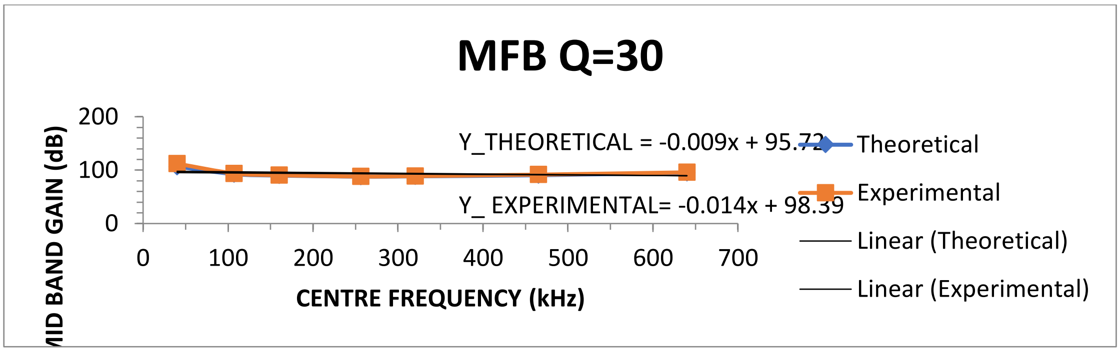


Figure 6: Comparison of Theoretical and Experimental Maximum Pass band Gain for MFB Topology at Q=30

Bandwidth

Results obtained and presented in Table 3 for the theoretical result was compared with the result presented in Table 5 for the experimental result of the eighth –order active – R bandpass filter using MFB topology at varying centre frequencies F_o and constant quality factor of Q = 25 using filter characteristics of bandwidth. The plot is shown in Figure 7. Figure 7 shows the comparison of the bandwidth of the eighth-order active-R bandpass filter using MFB topology at a quality factor of Q = 25 and varying centre frequencies using theoretical and experimental values. The plot shows the variation of the bandwidth obtained from the theoretical values to be higher with a value of 0.853 kHz at F_o= 40 kHz that increased geometrically to 23.456 kHz at F_o= 640 kHz compared to the experimental values that increased from 0.210 kHz at F_o= 40 kHz to 20.63 kHz at F_o= 640 kHz. The trend shows that both the theoretical and experimental filters had an increasing trend which can be confirmed from positive slope of the trend equations in the plot. We observed from the Figure that, the theoretical values had much higher bandwidth compared to the experimental values even though they have the same trend. However in terms of bandwidth, the filter with the lower values is deemed to have better selectivity than the filter with a much higher value, therefore the experimental filter can be said to have better selectivity than the theoretical filter.

Results obtained and presented in Table 4 for the theoretical results was compared with the results presented in Table 6 for the experimental results of the eighth –order active-R bandpass filter using MFB topology at varying centre frequencies F_o and constant quality factor of Q=30 using filter characteristics of bandwidth is shown in Figure 8. The plot shows that the theoretical values obtained were higher with a value of 0.959 kHz at F_o=40 kHz that increased spontaneously to 25.10 kHz at F_o= 640 kHz compared to the experimental values which were much lower with a value of 0.343 kHz at F_o=40 kHz and increased to 23.53 kHz at F_o=640 kHz. We also observed that both filters had the same increasing trend judging from the positive slopes in the trend equations. The theoretical values were a little higher than the experimental values again confirming that the experimental filter had better selectivity than the theoretical filter.

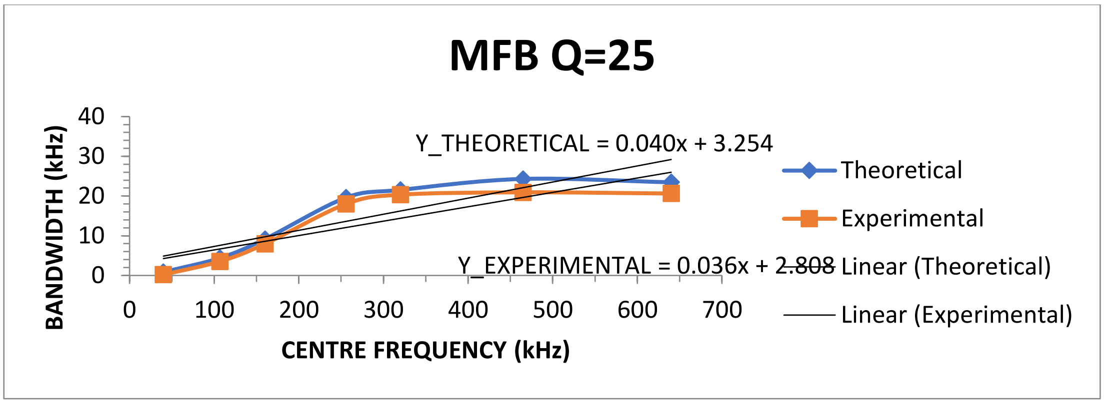


Figure 7: Comparison of Theoretical and Experimental Bandwidth for MFB Topology at Q=25

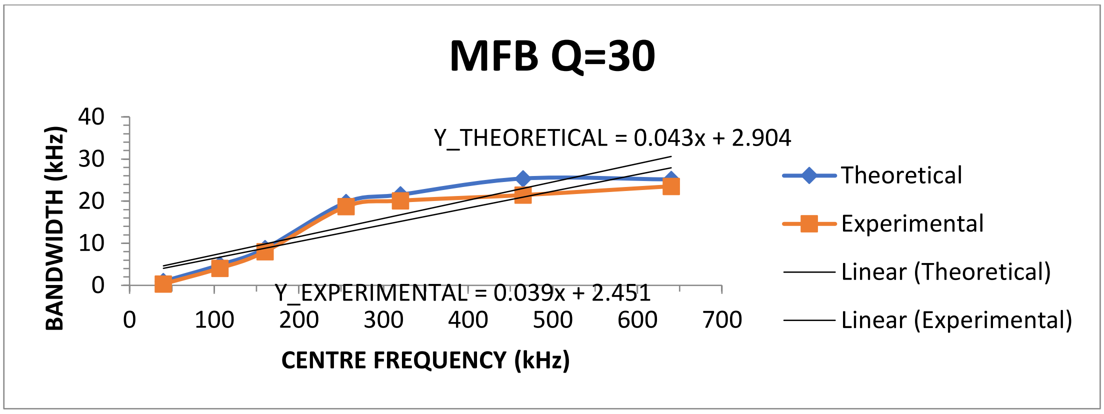


Figure 8: Comparison of Theoretical and Experimental Bandwidth for MFB Topology at Q=30

Roll-off rate

Results obtained and presented in Table 3 for the theoretical results was compared with the results presented in Table 5 for the Experimental results of the eighth –order active-R bandpass filter using MFB topology at varying centre frequencies F_o and constant quality factor of Q = 25 using Filter characteristics of roll-off rate is shown in Figure 9. The plot shows an increasing trend for both theoretical and experimental filters from the positive slopes of the trend equations. The least theoretical value is -73.226 dB/decade at F_o= 40 kHz and the highest value is -48.087 dB/decade at F_o = 256 kHz while the least experimental value is -64.932 dB/decade at F_o=40 kHz, the highest value of -59.781 dB/decade at F_o=256 kHz. We observed from the plot that the experimental values for F_o= 40 kHz, F_o= 107 kHz and F_o= 640 kHz were higher than the theoretical values while the theoretical values from F_o=160 kHz to F_o=465 kHz were higher than the experimental values. From Figure 9, we can see that both filters behaved like single pole third-order filters with very poor roll-off rates contrary to an eighth-order filter of interest.

Results obtained and presented in Table 4 for the theoretical results was compared with the results presented in Table 6 for the Experimental results of the eighth –order active-R bandpass filter using MFB topology at varying centre frequencies F_o and constant quality factor of Q = 30 using filter characteristics of roll-off rate is shown in Figure 10. From the plot we observed that both the theoretical and experimental filters had increasing trend as the centre frequency increased, evident from the positive slopes of the trend equations. We observed from the plot that both filters behaved like third- order filters at every other frequencies except at F_o= 107 kHz where the theoretical filter behaved like a single pole eighth-order filter while the experimental filter behaved like a single pole fourth-order filter.

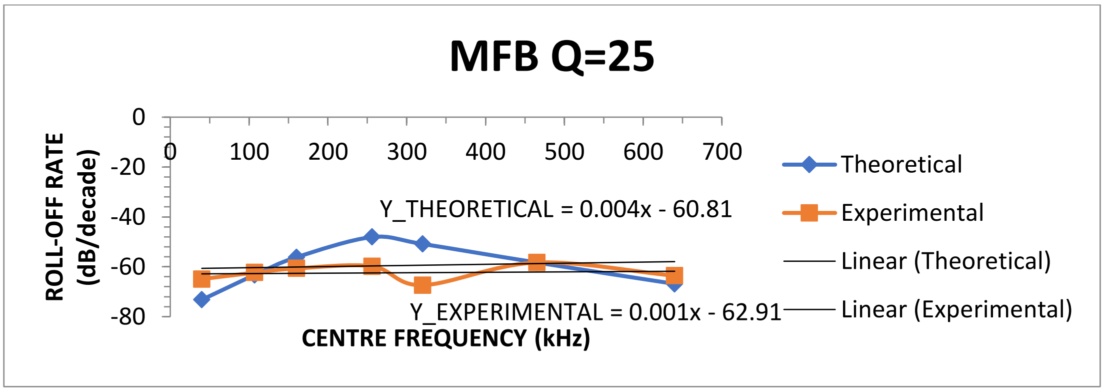


Figure 9: Comparison of Theoretical and Experimental Roll-Off Rate for MFB Topology at Q=25

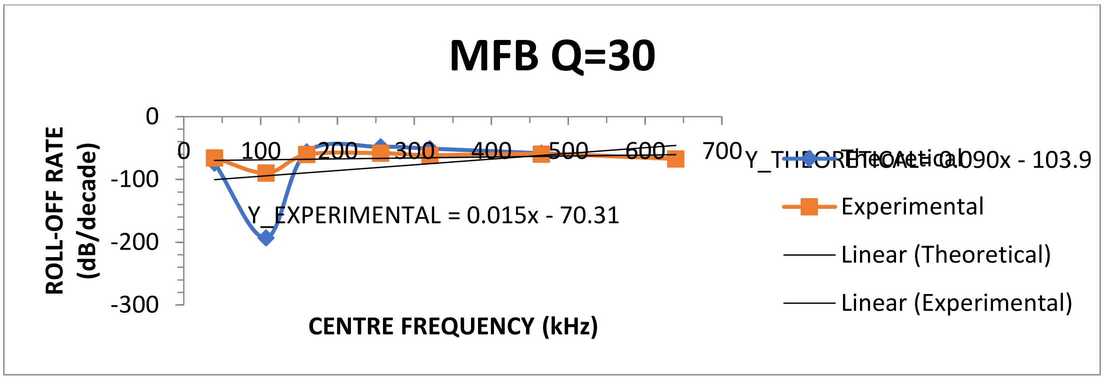


Figure 10: Comparison of Theoretical and Experimental Roll-Off Rate for MFB Topology at Q=30

The comparison of the theoretical and experimental results obtained as presented was made with each other; the following relationship was established;

i. MFB topology, for experimental and theoretical values at Q= 25 (Figure 56) and Q = 30, it was observed that, the trend of maximum pass band gain first decreased from F_o=40 kHz to F_o=256 kHz and then increased finally to F_o=640 kHz. This trend was consistent with each other, with the experimental values being higher than the theoretical values.
ii. MFB topology, for experimental and theoretical values at Q = 25 (Figure 58) and Q= 30, it was observed that the bandwidth of the MFB topology had increasing trend as the centre frequencies increased giving rise to a similar trend with the theoretical values. The theoretical values were higher than the experimental values. This can also be interpreted as the experimental values being more selective than the theoretical values.
iii. MFB topology for experimental and theoretical values at Q =25 (Figure 60) and Q = 30, it was observed that the roll off rate increased rapidly with increasing centre frequency up to F_o=256 kHz and then decreased rapidly to F_o= 640 kHz with the theoretical values while the experimental values increased gradually with increasing centre frequency at F_o=256 kHz then decreased gradually to F_o= 465 kHz and then increased at F_o= 640 kHz giving rise to a roll- off rate that provides a third order single-pole and fourth order single-pole as discussed previously. The roll- off rate for the quality factor of Q = 30, shows the values of theoretical and experimental values decreased at first before increasing up to F_o= 640 kHz with all the values approaching third and fourth order single pole roll- off.

CONCLUSION

The eighth-order active-R bandpass filter using MFB topology at variable centre frequencies and quality factors of Q = 25 and Q = 30 were designed and developed as presented above. The tag to reader transmission is performed in a frequency band commonly used in many other applications, which might interfere in the RFID communication. Therefore, taking into cognisance the wide range of link frequencies that the UHF EPC for UHF RFID allows to use, it is necessary to develop a filter with tight bandwidth to receive the RFID signal. The EPC standard for UHF RFID permits the communication from the RFID tag to the RFID reader in a modulation frequency that ranges from 40 kHz to 640 kHz. Therefore, from the submissions given above for all the Figures and Tables of results, we can see that in terms of maximum pass band gain (G_{max}), the multiple feedback topology gave a positive and much higher gain. In terms of bandwidth and roll-off rate, the multiple feedback had wider bandwidth and gave a roll-off rate that behaved like a third-order single pole and fourth-order single pole. These observations are consistent with previous reports. However the over shoot, the degradations and distortions noticed with the MFB topology discussed above all largely were caused by component values (parasitic effect) and the type of op. amp used. It is reported that higher quality factor (Q) values (i.e Q>10) create circuit instability and makes the circuit very sensitive to circuit component tolerances. Capacitors are the real accuracy controlling and variation controlling components and so, precise capacitors are required in multiple feedback topologies (MFB) like the one presented in this work. Apart from the capacitors, the MFB topology is particularly sensitive to the tolerance alternator resistance R_b and so requires precise resistors. Thus, the shift in centre frequency, distortion in the roll-off rate can be attributed to the high tolerance values of the resistors and the approximated values of the resistors in this design. The restriction to the commonly available resistors informed this approximation. In terms of the experimental and theoretical values, the experimental values were higher for the maximum pass band gain and the roll-off rates obtained. Except in terms of bandwidth where the theoretical values were better, this shows that the experimental procedure was highly controlled in the laboratory so as to achieve reasonable results.

RECOMMENDATIONS

The forward link communication (860MHz – 960MHz) between the receiver and the tag should be explored to compliment this work.

For better results to be achieved the values of the resistors R_{7b} and R_{7a} which controls the centre frequency and R_3 that controls the gain should be of low value so as to avoid the shifting of the centre frequency.

The resistor values used should be of 5% tolerance which is common and not 1% that is not common.

The filter should be first programmed since this will provide the fastest way to verify its proper functionality and make the appropriate adjustments and modifications before construction.

The error margins introduced in a study provide a quantitative measure of the discrepancies between the experimental and theoretical data. The results show that the experimental data are in good agreement with the theoretical data, with some discrepancies due to experimental uncertainties and parasitic effects. The error margins can be used to optimize the design of the filter and improve its performance. For example, the error margin for the bandwidth can be used to adjust the values of the resistors and capacitors to achieve a more accurate bandwidth. Therefore, the introduction of error margins for experimental vs. theoretical data provides a valuable tool for quantifying discrepancies and optimizing the design of the filter.

Here's an expanded analysis or explaining why the filter behaves as a third-order instead of eighth-order and suggesting possible design corrections. The roll-off rate analysis reveals that the filter behaves as a third-order instead of an eighth-order. This discrepancy can be attributed to several factors: Parasitic effects, such as capacitance and inductance, can significantly impact the filter's roll-off rate. The parasitic capacitance between the op-amp's input and output terminals can cause a pole-zero pair, leading to a reduced roll-off rate; Component tolerances can also contribute to the reduced roll-off rate. The tolerances of the resistors and capacitors can cause deviations in the filter's transfer function, leading to a lower-order response; The op-amp's limitations, such as its gain-bandwidth product (GBW) and slew rate, can also impact the filter's roll-off rate. The op-amp's GBW can cause a reduction in the filter's roll-off rate, while its slew rate can lead to distortion and non-linearity.

The Possible Design Corrections are;

To correct the design and achieve an eighth-order response, the following modifications can be made:

i. Reduce Parasitic Effects: Use a different op-amp with lower parasitic capacitance: Add shielding to reduce electromagnetic interference: Use a layout with shorter traces and fewer vias.
ii. Improve Component Tolerances: Use components with tighter tolerances (e.g., 1% instead of 5%): Use a different type of component (e.g., film capacitors instead of ceramic capacitors).
iii. Upgrade Op-Amp: Use an op-amp with a higher GBW and slew rate: Consider using a different type of amplifier (e.g., a current-feedback amplifier).
iv. Add Additional Stages: Add additional stages to the filter to increase its order and improve its roll-off rate: Use a different filter topology (e.g., a cascade of second-order stages instead of a single eighth-order stage).
v. By implementing these design corrections, it should be possible to achieve an eighth-order response and improve the filter's roll-off rate.

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