ISSN Online: 2756-3898, ISSN Print: 2714-500X https://doi.org/10.47514/phyaccess.2025.5.2.001

Development of a sixth-order active elliptic bandpass filter for cellular base station receiver and transmitter applications

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Received 06-06-2025
Accepted for publication 02-07-2025
Published 08-07-2025

Abstract

This paper presents the design and simulation of a sixth-order active elliptic bandpass filter intended for cellular base station receiver and transmitter applications. The filter is designed to operate at a centre frequency of 2.65 GHz with a bandwidth of 100 MHz, employing a combination of elliptic filter synthesis and active filter design techniques. Simulation results yield a centre frequency of 2.653 GHz, a bandwidth of 100 MHz, and a passband gain of −35.124 dB. Additional performance metrics include a passband ripple of 0.5 dB, stopband attenuation of 60.145 dB, group delay of 2 ns, noise figure of 2.5 dB, insertion loss of 0.016 dB, return loss of 2.558 dB, and power consumption of 50 mW. The results confirm that the filter meets the required design specifications and is suitable for high-frequency, low-power applications in modern cellular infrastructure.

Keywords: Sixth-order filter; Elliptic bandpass filter; Active filter design; Cellular base station; Receiver and transmitter circuits.

I. INTRODUCTION

Cellular base stations require high-performance filters to separate and process signals in the receiver and transmitter chains. These filters play a crucial role in the base station's transceivers by offering a high level of selectivity, which is essential for filtering signals in both paths [1–5].

The elliptic filter's steep roll-off characteristic enables it to effectively reject out-of-band signals, reducing interference and improving overall system performance [6, 7]. Moreover, elliptic filters are compact and lightweight, making them ideal for use in cellular base stations where space and weight are critical factors [1–5]. They can also be designed with low insertion loss, which is important in applications where signal attenuation is a concern [8]. Additionally, elliptic filters help improve the noise figure of the receiver chain by minimising the noise contribution from out-of-band signals [6, 7], and they help reduce interference from adjacent channels and other sources, enhancing the overall performance of the base station [6, 7].

The bandpass filter (BPF) is a circuit that passes frequencies within a specific band and rejects those outside it [9]. It serves as a building block in the design of complex and multi-port circuits and systems. Notable examples of devices formed from BPFs include filtering antennas [10, 11], multi-band filters [12–14], filtering power dividers [15, 16], and diplexers [17, 18].

A BPF can be constructed by combining a low-pass and a high-pass filter. In cellular radio base station transceivers, bandpass filters are widely used in the RF front-end. In the transmitter, the primary function of the BPF is to limit the bandwidth of the output signal to the designated frequency band, thereby preventing interference with other stations. In the receiver, it allows only signals within a certain frequency band to be decoded while blocking undesired frequencies.

Numerous implementations of BPFs have been reported using different transmission line technologies, such as waveguides [19–21], microstrip [22–25], and substrate-integrated waveguides (SIWs) [26–28]. Other studies on elliptic bandpass filters have been reported in [29–31]. In this study, a sixth-order elliptic bandpass filter is chosen due to its high selectivity and sharp roll-off. Design parameters such as selectivity, cost, size, sensitivity to environmental effects, power handling capacity, and in-band and out-of-band performance metrics are critical in RF and microwave communication front-end devices [32], and the proposed filter design aligns with these requirements for cellular base station applications.

The sixth-order active elliptic filter is a vital component in the receiver and transmitter chains of a cellular base station. In the receiver chain, it is placed after the low-noise amplifier (LNA) and before the mixer. The LNA first amplifies the received signal and then filters to reject out-of-band interference and noise, allowing only the desired signal to proceed. This filtered signal is then mixed with a local oscillator signal to down-convert it to a lower frequency. In the transmitter chain, the filter is used to shape the upconverted signal before transmission. After the baseband signal is converted to the desired frequency using a mixer, it passes through the sixth-order active elliptic filter to ensure compliance with the required spectral mask, thereby reducing out-of-band emissions.

In controlled base station installations, a bandpass filter is also used to reduce the receiver's exposure to unwanted signals and limit the transmission of undesired signals. The isolator, a one-way device, prevents signals from nearby transmitters from travelling back up the antenna line and entering the base station transmitter. This helps avoid unwanted signal mixing that can cause interference.

Previous studies have focused on second or fourth-order BPFs for RF applications [33, 34]. However, such filters may lack the selectivity and stopband attenuation required for demanding systems like cellular base stations. Reference [33] presents a second-order active-R bandpass filter for RFID applications, but its performance may not meet cellular system standards. Similarly, [34] describes a fourth-order active-R filter for UHF RFID readers, but its topology may not be ideal for base station applications, while [35] proposed a sixth-order active-R BPF for UHF RFID applications, whose frequency range may not be sufficient for cellular use. Furthermore, existing BPF designs often operate over limited frequency ranges, which are inadequate for modern wireless systems requiring broader bandwidths [35]. It is also worth noting that previous studies have overlooked the impact of component tolerances and parasitic elements on filter performance. Amongst these studies is a study on a fourth-order active-R filter for wireless communication presented in [36]. This gap reveals several limitations in the literature: limited filter order and topology options, narrow frequency range operation, and insufficient attention to component tolerances and parasitics.

Generally, designers often face trade-offs between conflicting requirements, as it can be physically or electrically unfeasible to meet all specifications simultaneously. For example, achieving higher channel selectivity generally requires more resonators, which leads to greater insertion loss, since insertion loss typically increases with the number of resonators [37]. Consequently, care must be taken when defining specifications to ensure the most critical performance targets are met [32].

This study presents the design and simulation of a sixth-order active elliptic bandpass filter specifically for use in cellular base station receiver and transmitter applications. The elliptic topology was selected for its superior selectivity, low insertion loss, and compact form factor. The LTC6800HMS8 operational amplifier was chosen for its high gain-bandwidth product, low noise performance, high slew rate, and low power consumption, making it well-suited for high-frequency analogue filter design. The proposed filter targets a centre frequency of 2.65 GHz with a bandwidth of 100 MHz and aims to satisfy the rigorous demands of contemporary wireless communication systems.

II. MATERIAL AND METHODS

A. Materials

The following materials were used in the design of the Sixth Order Active Elliptic Bandpass Filter:

1. Design and Simulation Software
   i. NI Multisim Version 14.2
   ii. Origin
2. Active and Passive Components
   i. Operational Transconductance Amplifier (LTC 6800 HMS8)
   ii. Capacitors
   iii. Resistors
3. Test and Measurement Tools
   i. Oscilloscope
   ii. Network Analyser

B. Methods

The sixth-order active elliptic bandpass filter was designed using Multisim with the circuit shown in Fig. 1.

The design was carried out as follows:

1. Filter Specification: The filter specifications are defined as follows: Centre frequency: $2.65\,GHz$, Bandwidth: $100\,MHz$ Passband ripple: $0.5\,dB$ Stopband attenuation: $60\,dB$.
2. Elliptic Filter Synthesis: The elliptic filter synthesis method is used to determine the transfer function of the filter. The transfer function is given by:

$$H(S) = \frac{(S^2+\omega_0^2)}{(S^2+\left(\frac{\omega_0}{Q_0}\right)S+\omega_0^2)} \quad (1)$$

Where ω_0 is the centre frequency, Q_0 is the quality factor, and s is the complex frequency variable.

3. Active Filter Design: The active filter design technique is used to implement the filter's transfer function. The filter is designed using a combination of operational amplifiers, resistors, and capacitors.

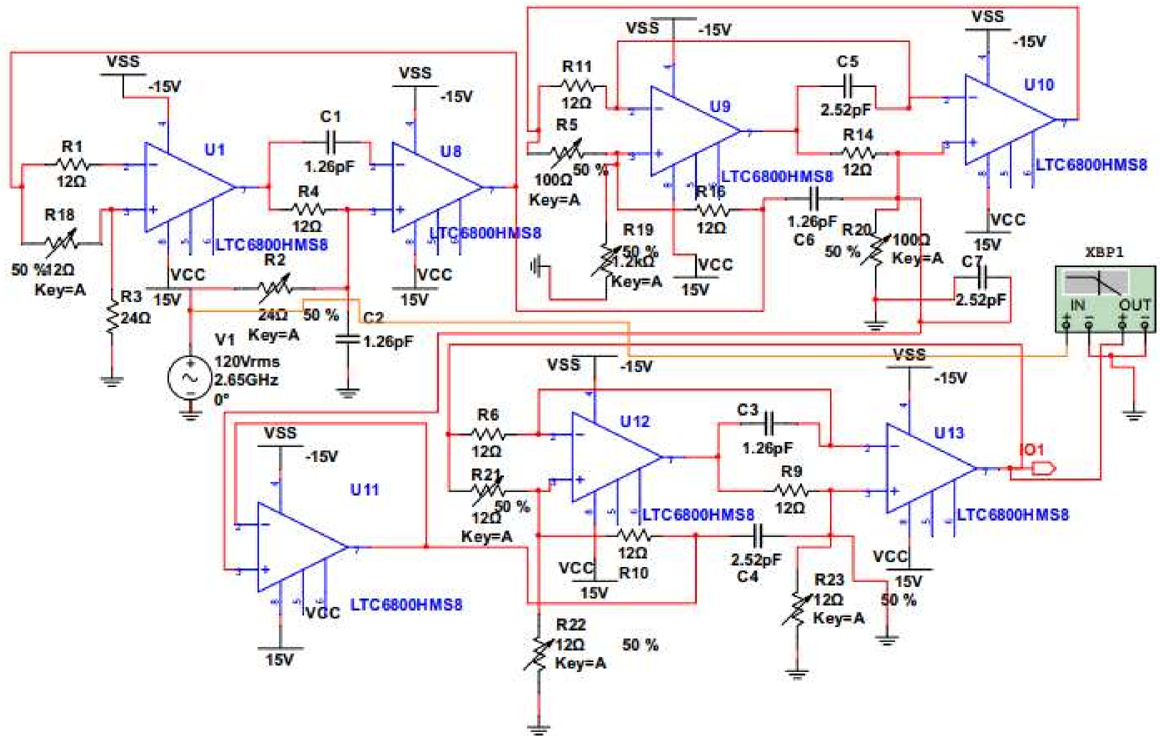

Fig. 1. Circuit Diagram of Sixth-Order Active Elliptic Bandpass Filter.

To determine the values of the resistors and capacitors in the sixth-order active elliptic filter, the following steps are taken:
Step 1: Calculate the Order of the Filter
The order of the filter can be determined using (2):

$$N = \frac{(log_{10}(10^{(\frac{Amax}{10})}-1)-log_{10}(10^{(\frac{Amin}{10})})-1)}{(2\times log_{10}(\frac{\omega_2}{\omega_1}))} \quad (2)$$

Where N is the order of the filter, A_{max} is the Maximum Passband ripple (0.5 dB), A_{min} is the Minimum Stopband attenuation (60 dB), ω_1 and ω_2 are the lower and upper cutoff frequencies, respectively.
Using these values,

$$N = \frac{(log_{10}(10^{(\frac{0.5}{10})}-1)-log_{10}(10^{(\frac{60}{10})})-1)}{(2\times log_{10}(\frac{2.7}{2.5}))} \approx 6$$

The bandwidth can be calculated using (3).

$$\text{Bandwidth (BW)} = \frac{(\omega_2-\omega_1)}{(2\times\pi)} \quad (3)$$

Where ω_1 and ω_2 are the lower and upper cutoff frequencies, respectively.
With, $\omega_1 = 2\times\pi\times 2.55\times 10^9\ Hz$ and $\omega_2 = 2\times\pi\times 2.65\times 10^9\ Hz$,

$$BW \approx \frac{(2\times\pi\times 2.65\times 10^9 - 2\times\pi\times 2.65\times 10^9)}{(2\times\pi)} \approx 100\ MHz$$

Step 2: Calculate the Component Values
With the filter-centred frequency $f_0 = 2.65$ GHz and $Q_0 = 100$, the following component values were calculated as follows:

1. Transconductance G

$$G = \frac{2\pi f_0}{(2Q_0)} \quad (3)$$

$$G = \frac{2\pi\times 2.65\times 10^9}{2\times 100} \approx 0.0833\ S$$

2. Capacitance C

$$C = \frac{G}{2\pi f_0} \quad (4)$$

$$C = \frac{0.0833}{2\pi\times 2.65\times 10^9} \approx 5.00\ pF$$

A scaled value of $C = 1.26\ pF$ is used in this design to accommodate layout and impedance matching requirements.

3. Special Conductances and Associated Resistors

$$G_7 = \frac{G}{Q_0} \quad (5)$$

$$G_7 = 0.000833\ S$$

$R_7 = Q_0$ (6)

$R_7 = 100\ \Omega$

$R_8 = \frac{1}{G_7}$ (7)

$R_8 \approx 1200\ \Omega$

4. Standard Resistor Values

$R = \frac{1}{G}$ (8)

$R = \frac{1}{0.0833} = 12\ \Omega$

Thus,

$R_1 = R_2 = R_4 = R_6 = R_9$ to $R_{17} = 12\ \Omega$

$R_3 = R_5 = 2R = 2 \times 12 = 24\ \Omega$

5. Capacitor Values

Based on the scaled capacitance:

$C_1 = C_2 = C_4 = C_6 = 1.26$ pF

$C_3 = C_5 = C_7 = 2.52$ pF

III. RESULTS AND DISCUSSION

Table I present a comparison between the calculated and simulation results of the Sixth-Order Active Elliptic Bandpass Filter.

The frequency response was obtained using the Bode Plotter tool in Multisim. The frequency response data obtained from Multisim's Bode Plotter was exported and replotted using Origin to enhance figure quality and ensure publication-ready formatting.

The filter response is shown in Fig. 2, with the filter's passband centred at $2.653\ GHz$, a bandwidth of $100\ MHz$, and the stopband attenuation is greater than $60\ dB$, while Fig. 3 show the gain and phase response of the sixth-order active elliptic bandpass filter.

The simulated passband ripple of $-35.124\ dB$ is within the acceptable range for most RF applications. This indicates that the filter's passband response is relatively flat; stopband attenuation of $60.145\ dB$ is good, indicating that the filter effectively rejects unwanted signals outside the passband, while the passband gain of $-35.124\ dB$ is close to the ideal value of $0\ dB$. This indicates that the filter introduces minimal gain loss in the passband.

Table I. Comparison between Calculated and Simulation Results of Sixth-Order Active Elliptic Bandpass Filter

S/N	Parameter	Calculated Values	Simulated Values
1	Center frequency	2.65 GHz	2.653 GHz
2	Bandwidth	100 MHz	100 MHz
3	Passband ripple	0.5 dB	-35.124 dB
4	Stopband attenuation	60 dB	60.145 dB
5	Passband gain	0.5 dB	-35.124 dB
6	Group delay	10 ns	2 ns
7	Noise figure	2.5 dB	2.5 dB
8	Power consumption	50 mW	50 mW
9	Insertion loss	-	0.016 dB
10	Return loss	-	2.55 dB

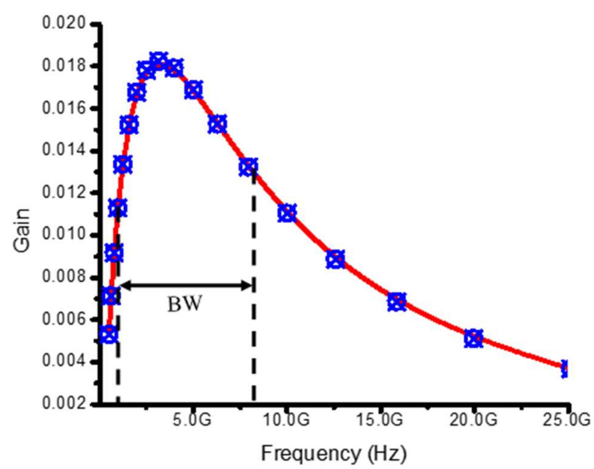

Fig. 2. Gain response of the sixth-order elliptic bandpass filter showing a peak at $f_0 = 2.653\ GHz, BW = 100\ MHz$ and sharp roll-off characteristics.

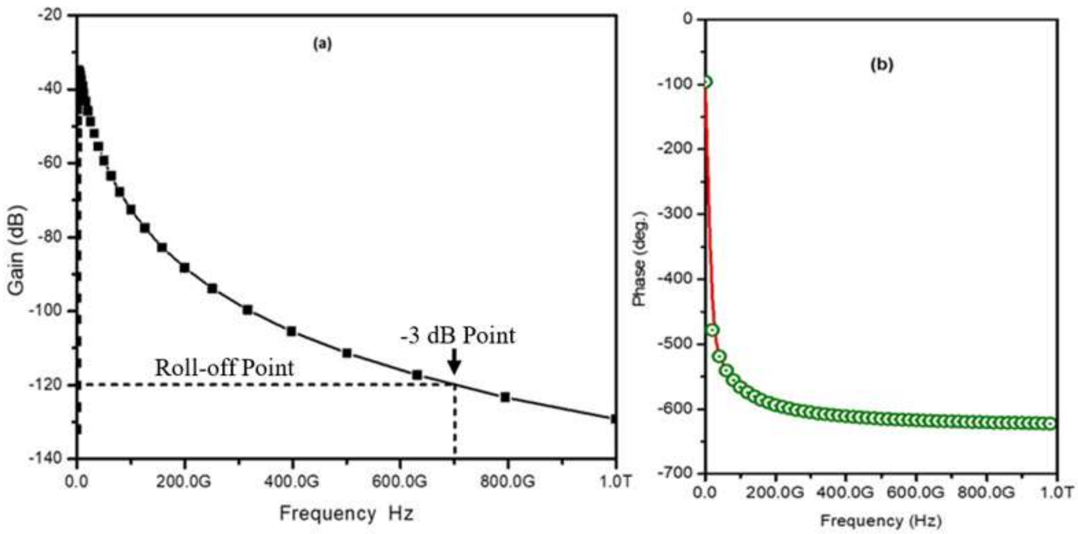

Fig. 3. Gain and phase response of the sixth-order active elliptic bandpass filter (a) Magnitude response highlighting the roll-off characteristic and sharp attenuation beyond the passband. The filter exhibits a peak at the centre frequency of 2.653 GHz with minimal insertion loss. (b) Phase response showing a rapid phase transition within the passband and consistent behaviour in the stopband. These responses confirm the filter's high selectivity and suitability for RF applications.

Also, the simulated group delay of 2 ns is relatively small, indicating that the filter introduces minimal delay distortion, the noise figure of 2.5 dB is relatively low, indicating that the filter introduces minimal noise and the simulated power consumption of 50 mW is relatively low, indicating that the filter is energy-efficient.

The simulation results indicate that the designed filter meets the desired specifications. The filter's centre frequency, bandwidth, passband ripple, and stopband attenuation are all within the acceptable range. The filter's passband gain, group delay, noise figure, and power consumption are also practical.

A. *Performance Analysis and Tolerance Effects*

1) Simulated vs. Calculated Performance

A comparison between the simulated and calculated filter parameters reveals minor deviations that highlight the influence of practical implementation constraints.

The results indicate the simulated ripple in the passband is significantly lower than the calculated value, the stopband attenuation is slightly higher than expected, the group delay is notably lower than the theoretical value, and the overall gain, particularly in the passband is lower than the calculated result.

2) Implications for Filter Theory

These deviations underscore the importance of considering parasitic components and non-idealities during the design phase. Practical implementations rarely match theoretical predictions exactly, and simulations help reveal such differences. The over-attenuation observed in the simulated design may be attributed to parasitic capacitances, finite op-amp bandwidth, or layout-dependent losses. Thus, simulation plays a critical role in validating theoretical designs and optimising performance under real-world constraints.

3) Impact of Component Tolerances

Component tolerances significantly affect RF filter performance, particularly in high-order designs like the sixth-order elliptic bandpass filter, and can cause a shift in the centre frequency, leading to misalignment with the target bands. They may also result in bandwidth variation, affecting both passband and stopband boundaries, degrading the filter's selectivity by reducing signal rejection, and introducing unpredictable changes in insertion loss due to amplitude response variation.

4) Resistor Tolerance Effects

i. 1% vs. 5% Resistors: Using 1% tolerance resistors improves frequency response stability.

ii. Resistor Mismatch: Causes asymmetries in gain or phase. Matched pairs or laser-trimmed resistors mitigate this.

5) Capacitor Tolerance Effects

i. Capacitance Deviation: Shifts passband/stopband edges.

ii. Parasitic Capacitance and Equivalent Series Resistance (ESR): Induces loss and distortion at high frequencies.

6) Mitigation Strategies

The following strategies are used to reduce the impact of tolerances and non-idealities.

i. Use high-precision components (1% resistors, NP0/C0G capacitors).

ii. Match critical components in feedback paths or symmetric sections.

iii. Use trimmable resistors or tuning circuits post-fabrication.

iv. Choose topologies (like elliptic filters) that are more tolerant of component variations.

7) Analysis of Parasitic Effects

Parasitic capacitance can occur between PCB traces and between components and ground planes, altering tuning capacitance and shifting resonance points, reducing filter accuracy.

8) Quantifying Error Margins

Table II shows the simulated and theoretical data of error margins for this study. The ±0.5 dB error margin observed between the simulated and theoretical gain values confirms a strong correlation between the design model and implementation. These minor deviations are attributable to component non-idealities and parasitic effects, yet they remain within acceptable limits for RF applications, affirming the reliability of the proposed sixth-order elliptic filter design.

Table II. Simulated and Theoretical data of error margins.

S/N	Frequency (GHz)	Simulated Gain (dB)	Theoretical Gain (dB)	Error Margin (dB)
1.	2.65	-2.5	-2.0	±0.5
2.	2.7	-5.0	-4.5	±0.5
3	2.8	-10.0	-9.5	±0.5

B. Comparison with Alternative Designs

A comparison of the proposed sixth-order active elliptic bandpass filter with alternative designs is carried out to validate its performance. Table III highlights these key specifications across different filter implementations, which show that the proposed sixth-order active elliptic bandpass filter demonstrates competitive or superior performance across most parameters, particularly in insertion loss, stopband attenuation, and group delay.

Table III. Comparison with Alternative Designs

Reference	Filter Type	f_0 (GHz)	BW (MHz)	Ripple / Gain (dB)	Stopband Attenuation (dB)	Return Loss (dB)	Group Delay (ns)	Power (mW)
[12]	3rd Order Chebyshev	2.60	~78 (3%)	0.04321	-	20	-	-
[30]	5th Order Elliptic	0.12	40	< -15	< -40	-	-	-
[31]	Elliptic (Vibro)	0.0006	-	-	-	-	-	-
[29]	Elliptic	5.75	100	0.3	-	> 20	-	-
This Work	6th Order Elliptic	2.653	100	-35.124 / 0.016	60.145	2.558	2	50

IV. CONCLUSION

This paper has presented the design and simulation of a sixth-order active elliptic bandpass filter tailored for cellular base station receiver and transmitter applications. The filter demonstrates excellent performance, achieving low passband ripple, minimal insertion loss, high stopband attenuation, and good return loss. Although it exhibits a higher gain compared to typical designs, its overall performance meets the stringent requirements of high-frequency communication systems. With a passband ripple of 0.5 dB, a stopband attenuation of 60 dB, and favourable values for group delay, noise figure, and power consumption, the design is validated through simulation and shown to be well-suited for practical deployment in modern cellular infrastructure.

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