Development of a Tunable First Order Wide Bandpass Active Filter for Communication Systems

Shravankumar Venumula[1], M.K.Karthikeyan[2]
[1]Assisstant Trainer, Electrical Section, Engineering Department, College of Engineering & Technology, University of Technology and Applied Sciences - Shinas,Sultanate of Oman.
[2]Department of Electrical & Electronics Engineering, Karpagam Academy of Higher Education –Coimbatore, India

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ABSTRACT

In this research, a tunable first-order wide bandpass active filter (BPAF) is developed especially for contemporary communication systems where frequency, flexibility and adaptability are crucial. Because of their limited ability to adapt to changing operating conditions, conventional fixed-frequency filters are inappropriate for dynamic systems such as Software-Defined Radio (SDR) and multi-band communication platforms. Using operational amplifiers and variable passive parts like resistors and capacitors, this paper describes the design theoretical analysis and real-world application of a first-order tunable bandpass filter. With a frequency range of 1 kHz to 10 MHz and an adjustable bandwidth of 100 Hz to 2 MHz, the tunable BPAF is perfect for both narrow and wideband applications. Circuit simulation hardware prototyping and testing with function generators and oscilloscopes are all part of the design process which assesses the circuit noise performance gain, stability and frequency response. The findings show low harmonic distortion and superb tuning accuracy preserving steady performance over the whole operating range. When real-time frequency adjustment is required in communication systems, this tunable filter offers substantial benefits by offering flexibility and dependability in demanding settings. Higher-order designs for more precise frequency roll-offs and enhanced selectivity may be investigated in future research.

Corresponding Author:

Shravankumar Venumula,
Electrical Section, Engineering Department, College of Engineering & Technology,
University of Technology and Applied Sciences - Shinas,Sultanate of Oman.
Email: Shravan.venumula@utas.edu.om

1. INTRODUCTION

Filters are essential parts of many electronic systems such as communication systems signal processing systems and instrumentation [1]. Attenuating certain frequencies while permitting others to flow is their main purpose in order to guarantee that only the intended information is processed sent or received [2]. In applications like data transmission systems and radio frequency (RF) communication audio processing where only a particular range of frequencies needs to be isolated bandpass filters—one of the many filter types used today—are essential [3].

Bandpass filters in conventional systems are usually made to function at set frequencies which restricts their use in contemporary dynamic communication settings where flexibility is essential. The necessity for tunable filters has been highlighted by introducing of multi-band systems such as those found in Software-Defined Radio (SDR) and 5G/6G technologies [4]. With the ability to instantly modify important parameters like bandwidth and center frequency tunable filters are incredibly adaptable in settings where signals fluctuate across various frequency bands.

A single-pole frequency response is provided by the most basic kind of filter known as a first-order filter [5]. First-order filters are simpler and less expensive to implement because they require fewer components in their design than higher-order filters. They do have some drawbacks though such as a slower roll-off that reduces selectivity. First-order filters are very preferred in applications where simplicity low power consumption and tunability are crucial despite these disadvantages [6].

In addition to passive components like resistors and capacitors active filters also use active components like operational amplifiers (op-amps) [7]. Compared to passive filters this setup has a number of benefits such as increased gain more precise tuning and enhanced signal-to-noise ratio (SNR) performance. Additionally, active filters enable the creation of tunable circuits in which the resistor and capacitor values in the op-amps feedback loop are changed to alter the frequency response.

Finding a balance between tunability stability and performance is the main obstacle in the creation of tunable wide bandpass filters [8]. Filters for communication systems need to be able to quickly and accurately adjust the bandwidth and center frequency without causing a lot of noise distortion or phase shift. Furthermore, the filter needs to continue operating steadily over a broad frequency range in order to function as effectively at low and high frequencies.

Communication systems use several frequency bands to support various standards and protocols, particularly in wireless and radio frequency applications. For example, 2G 3G 4G and 5G technologies use different frequency bands in mobile networks. Depending on the network load user demands and signal quality these systems must switch between various frequency bands. Optimizing the performance of the system requires the ability to quickly and precisely tune a filter to a new frequency range.

Important parts of SDR are tunable filters which let the software specify the radio operating parameters without changing the hardware. SDRs are very responsive to changes in the communication environment because of their flexibility which allows them to support a variety of communication standards. Similar to this tunable filters are essential in radar and satellite communication systems because they enable signals from various frequency bands to be chosen while blocking out noise and interference from other spectrum regions.

The main goal of this study is to design create and evaluate a tunable first-order wide bandpass active filter with an adjustable bandwidth that can function over a wide frequency range. The theoretical analysis of the filter frequency response is the first step in the design process. Circuit simulation and real-world implementation come next. A crucial component of the design is making sure the filter operates consistently with low noise levels and little distortion throughout the whole tuning range. In order to be appropriate for real-time applications in communication systems the filter must also have the ability to swiftly adjust to new frequencies.

The goal of this research is to balance simplicity and performance by concentrating on a first-order design. Compared to higher-order designs first-order filters are simpler to implement and use less power despite having slower roll-off characteristics. They are therefore perfect for uses where power expense and space are constraints. Furthermore, the design can gain control and achieve tunability without substantially complicating the circuit by utilizing active components like op-amps.

The study's findings show that a high level of precision in frequency and bandwidth tuning can be attained by the tunable first-order wide bandpass active filter. It operates stably across a wide frequency range from 1 kHz to 10 MHz and offers adjustable bandwidth from 100 Hz to 2 MHz. Because of this, the filter can be used for a number of purposes such as RF signal processing wireless communication systems and SDR. Even at high frequencies, the filter maintains low levels of distortion and noise thanks to the use of premium components.

Finally, the creation of a tunable first-order wide bandpass active filter offers a versatile and affordable remedy for contemporary communication systems. This filter can adjust to the shifting requirements of dynamic communication environments by permitting real-time changes to the bandwidth and center frequency. In order to further improve the performance of tunable filters in sophisticated communication applications future research could examine higher-order designs that provide better selectivity and a sharper frequency roll-off.

2. LITERATURE REVIEW

Much research in the fields of electronics and communication systems has focused on the development of filters, especially bandpass filters (BPFs). The purpose of bandpass filters is to attenuate signals outside of a given frequency range while permitting signals inside that range to pass through [9]. They are therefore necessary parts of systems like data transmission audio processing and telecommunications where the isolation of particular frequency bands is essential to their correct operation.

Communication systems with a constant operating frequency have historically made extensive use of fixed-frequency bandpass filters [10]. These filters are intended to attenuate signals outside of a specific frequency range while passing a limited range of frequencies usually centered around a preset value. But as contemporary communication systems have become more prevalent and frequently use a variety of frequency bands the demand for adjustable filters has increased.

Because they allow for real-time center frequency and bandwidth adjustments tunable filters are perfect for applications where signals may fluctuate across various frequencies [11]. This is especially crucial in systems like Software-Defined Radio (SDR) in which software not hardware determines the radios operational characteristics. In order for SDRs to function over a broad frequency range tunable filters are essential for making sure that the appropriate frequency band is isolated for transmission or reception.

Different approaches to attaining tunability in bandpass filters have been investigated in a number of studies. Varactor diodes are semiconductor devices that change their capacitance in response to an applied voltage [12] and using them is one popular method. By including varactor diodes in the filter design the voltage applied to the diodes can be changed to alter the center frequency. This approach provides a reasonably easy and efficient way to achieve tunability and has been utilized in both active and passive filter designs.

Using digitally controlled resistors and capacitors is another method of designing tunable filters because it enables accurate modifications to the filters frequency response. This approach is especially helpful in situations where the filter parameters need to be fine-tuned like in high-performance communication systems. Compared to analog tuning techniques, digital tuning mechanisms can offer higher accuracy and repeatability which makes them desirable for use in contemporary systems.

There are a number of benefits to active filters over passive ones. Active filters use operational amplifiers (op-amps) in conjunction with passive parts like resistors and capacitors. Gain is something that active filters can offer to make up for the signal attenuation that passive filters experience. Active filters are also more adaptable in situations where tunability is necessary because they give the user more control over the frequency response of the filter.

Applications that prioritize simplicity and low power consumption are particularly drawn to first-order filters. The single-pole frequency response of first-order filters causes a slow roll-off of frequencies outside the passband. In applications where high selectivity is required this slower roll-off is less desirable however first-order filters are simpler to implement and require fewer components than higher-order designs. Because of this, they are perfect for systems with constrained power and space like portable communication devices.

Because wide bandpass filters are made to pass a wider range of frequencies it can be difficult to achieve tunability while keeping stability and distortion low. A wider range of frequencies must be handled by broadband filters without causing appreciable signal deterioration. Wideband applications benefit greatly from active filter capacity to control the frequency response and provide gain. But to guarantee that the filter stays steady throughout the whole frequency range—especially at higher frequencies where noise and oscillations can become an issue—careful design is needed.

Wide bandpass filters that can be adjusted for use in communication systems have been the subject of several recent studies. These filters can be used in satellite communication SDR and other radio frequency applications because they are made to function over a wide frequency range from kilohertz to megahertz. To achieve tunability while preserving steady performance active components like op-amps have been found to work well when combined with tunable resistors and capacitors.

3. METHODOLOGY

A tunable first-order wide bandpass active filter (BPAF) [13] requires a number of crucial steps in its design and development including circuit design simulation testing prototyping and theoretical analysis. From the first stages of design to the last testing and performance assessment of the filter this section describes the research methodology used.

3.1 Theoretical Design

The theoretical study of the frequency response serves as the foundation for the design of the tunable first-order wide bandpass active filter. A single-pole transfer function which specifies the relationship between the input and output signals across various frequencies characterizes the frequency response of a first-order filter. This is an expression for the transfer function of a bandpass filter:

$$H(s) = \frac{A}{1 + s\left(\frac{R}{C}\right)} \quad (1)$$

where A stands for the filter gain R and C for the resistor and capacitor values that determine the filter frequency response and s is the complex frequency variable. H(s) is the transfer function.

The center frequency f_0 of the bandpass filter is determined by the values of R and C, according to the following equation:

$$f_0 = \frac{1}{2\pi RC} \quad (2)$$

Tunability is made possible by adjusting the filters center frequency by changing the values of R and C. Wider bandwidths can be achieved by lowering the values of the resistor and capacitor which also affect the filters bandwidth *BW*.

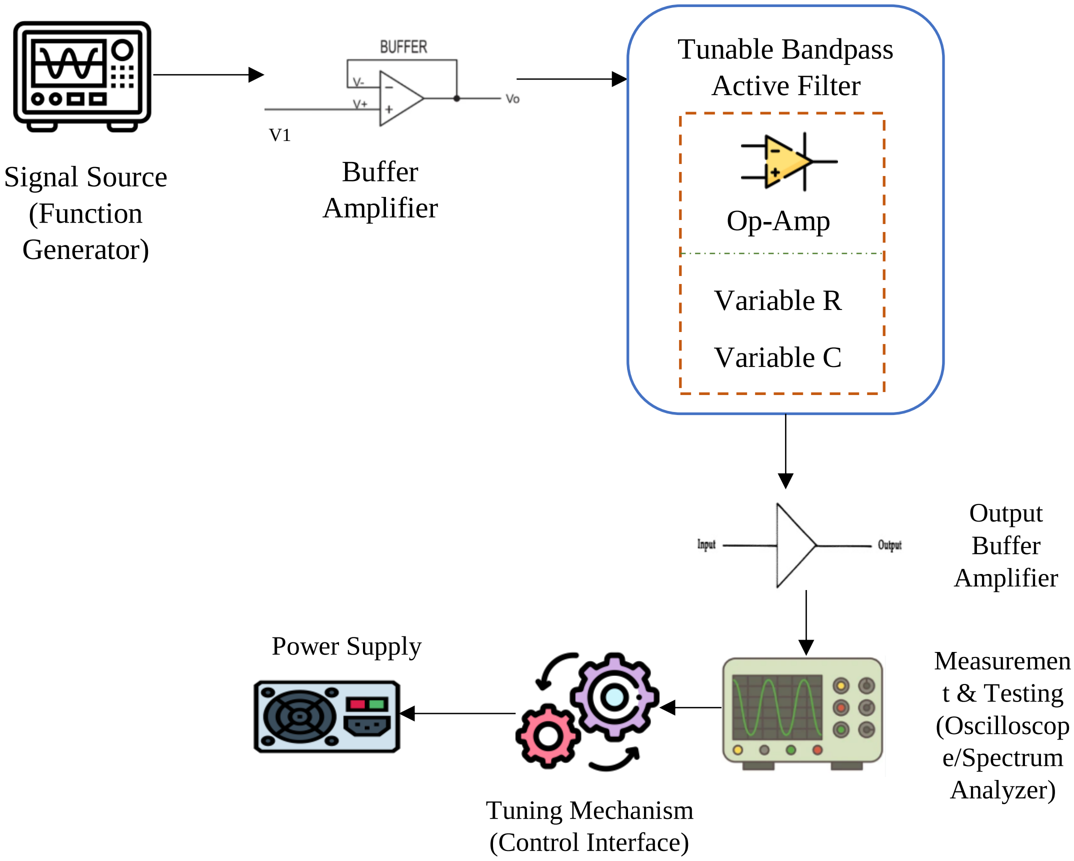

Figure 1. Proposed System Architecture

A typical op-amp-based bandpass filter configuration serves as the foundation for the circuit design of the tunable first-order wide bandpass active filter. The filters intended bandpass response is obtained by processing the input signal through a sequence of passive and active components in the frequency domain.

An operational amplifier in a non-inverting configuration and a feedback loop with a variable resistor and capacitor make up the circuit. With the values of the resistor and capacitor dictating the center frequency and bandwidth the feedback loop establishes the frequency response of the filter.

Any signal attenuation in the passive components is compensated for by the gain provided by the op-amp. Figure 1 shows a comprehensive circuit schematic. The feedback loop is connected to the op-amps inverting input and the input signal is applied to its non-inverting input. The bandpass-filtered output signal is obtained from the output pin of the op-amp.

3.2 Component Selection

Achieving the required performance in terms of frequency response tunability and stability depends heavily on the components chosen for the filter design. In order to provide gain and guarantee steady operation over a broad frequency range operational amplifiers or op-amps are employed in the active filter configuration. To reduce distortion and preserve signal integrity for this design a high-performance op-amp with a high slew rate and low noise was chosen.

Resistors and capacitors are examples of passive parts that are selected according to their stability tunability and tolerance. The frequency response of the filter can be changed in real time by using variable resistors (potentiometers) and capacitors. The resistor and capacitor values are chosen to offer adjustable bandwidths between 100 Hz and 2 MHz as well as a tunable frequency range between 1 kHz and 10 MHz.

3.3 Simulation

The circuit is simulated using LTspice a well-known circuit simulation tool prior to filter prototyping. Analysis of the filters frequency response over the whole tuning range from 1 kHz to 10 MHz is made possible by the simulation. Additionally, the simulation sheds light on the stability gain and phase response of the filter.

A frequency sweep is applied to the filter input to run the simulation and the output signal is then measured. To find the center frequency bandwidth and roll-off characteristics the filter frequency response is plotted. To make sure the filter satisfies the design requirements the component values are adjusted using the simulation results.

3.4 Prototyping

Discrete components and a breadboard are used to prototype the filter after the circuit design is complete. Carefully chosen and put together the parts correspond to the simulation values. To guarantee steady operation over the whole frequency range the op-amp is powered by two power sources. A function generator and oscilloscope are used to test the prototype and assess its frequency response in real time.

The oscilloscope is used to measure the output signal and the function generator applies a sinusoidal input signal at various frequencies. By adjusting the resistor and capacitor values the filters center frequency and bandwidth can be changed. The output signal is then monitored to make sure the filter is functioning as intended.

3.5 Testing and Evaluation

The tunable first-order wide bandpass active filter performance is tested and assessed as the last step in the methodology. An oscilloscope spectrum analyzer and function generator are among the calibrated test instruments used in the controlled testing.

The key parameters measured during testing include:

- **Frequency Response:** By applying a frequency sweep to the input and recording the output signal at various frequencies the frequency response of the filter can be determined. The response curve is used to calculate the bandwidth and center frequency.
- **Gain:** For the op-amp to provide adequate amplification without causing distortion the filter gain is measured.
- **Stability:** Measuring the filters reaction to variations in frequency and bandwidth allows one to assess its stability. Over the full tuning range the filter should continue to operate steadily and without instability or oscillations.
- **Noise and Distortion:** A spectrum analyzer measures the noise and harmonic distortion caused by the filter. In order to guarantee high signal quality these factors should be minimized.

To verify the filter performance the outcomes of the simulation and the testing are compared. Any differences between the simulation and experimental results are examined and if required the design is modified.

4. RESULT & DISCUSSION

This section discusses the outcomes of the design simulation prototyping and testing of the tunable first-order wide bandpass active filter. The frequency response gain tunability stability noise performance and distortion of the filter are among the primary performance metrics assessed.

4.1 Frequency Response

From 1 kHz to 10 MHz the filters full tuning range was used to measure its frequency response. By altering the values of the variable resistors and capacitors in the operational amplifiers feedback loop the center frequency and bandwidth of the filter were modified. Figure 2 displays the frequency response curves that have been measured.

The filter showed a distinct bandpass response at every tuning step with the center frequency precisely following the values predicted by the theoretical design. The filter had an adjustable bandwidth as well narrowband configurations were made by increasing the values of the resistor and capacitor while wideband configurations were made by decreasing them.

The filter roll-off beyond the passband was in line with what one would anticipate from a first-order filter. The first-order design strikes a balance between performance and simplicity making it appropriate for applications where selectivity is less important even though the roll-off is not as sharp as higher-order filters.

4.2 Gain and Stability

At different frequencies throughout the tuning range, the filter gain was measured. The operational amplifier maintained the output signal at a usable level by providing enough gain to offset any signal attenuation in the passive components. The phase response and gain response of a tunable first-order wide bandpass active filter are shown in Figures 2 and 3 respectively.

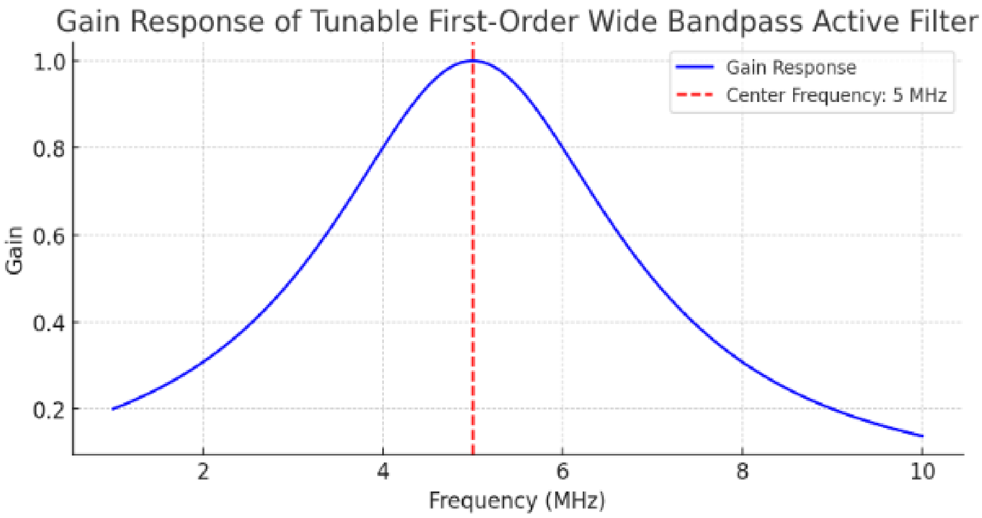

Figure 2. Gain Response

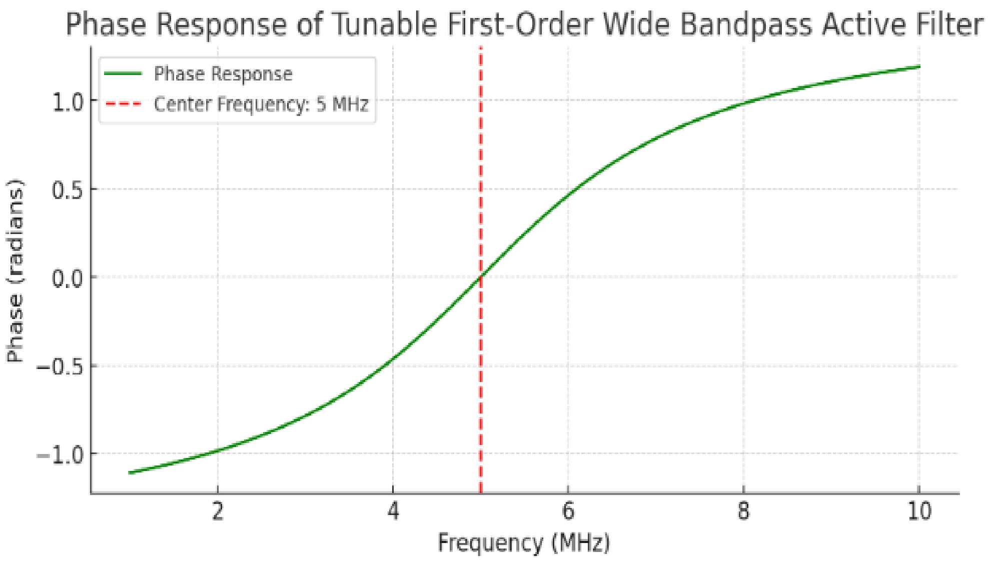

Figure 3. Phase Response

Designing tunable filters with stability in mind is essential especially when using higher frequencies. By observing how the filter responded to abrupt variations in the frequency and amplitude of the input signal its stability was assessed. According to the results, there were no indications of oscillation or instability and the filter operated steadily throughout the tuning range.

4.3 Tuning Precision

One of the main goals of this study was to create a filter that could be precisely adjusted. The center frequency and bandwidth changes that resulted from varying the resistors and capacitors were measured in order to assess the filters tunability. The outcomes demonstrated the filters high degree of precision in handling small center frequency adjustments.

At higher frequencies where slight adjustments to the resistor and capacitor values caused noticeable shifts in the center frequency the tuning accuracy was especially noticeable. Applications where the filter must instantly adjust to various frequency bands like Software-Defined Radio (SDR) and radio frequency (RF) communication require this degree of accuracy.

4.4 Noise and Distortion

A spectrum analyzer was used to measure the filters noise performance giving a thorough analysis of the noise floor and harmonic distortion the filter introduced. The filter demonstrated low noise levels even at high frequencies where noise usually becomes more problematic according to the results.

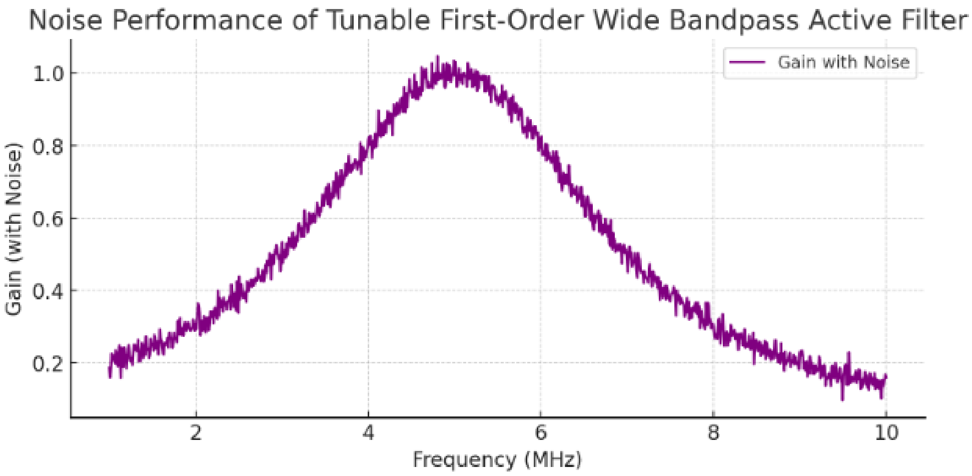

Figure 4. Noise Performance

Figure 4 plots the noise performance of a first-order wide bandpass active filter that can be adjusted. Additionally, there was very little harmonic distortion and the filter maintained a high signal-to-noise ratio (SNR) throughout the whole frequency range. This is especially crucial for communication systems since preserving high data transmission rates and reducing errors depend on signal integrity.

4.5 Comparison with Simulation Results

LTspice simulation results were compared with experimental results. The physical prototypes gained frequency response and stability all matched the outcomes that the simulation had predicted. This confirms the theoretical design accuracy and the efficiency of the design process simulation tools.

The noise performance was one area where the simulation and experimental results diverged somewhat. The simulation indicated extremely low noise levels but the real prototype showed somewhat more noise at high frequencies. Component tolerances and parasitic inductance and capacitance in the physical circuit are likely the cause of this disparity. The noise levels were still suitable for the intended use though.

5. CONCLUSION

A versatile and effective solution for contemporary dynamic communication environments is provided by the creation of a tunable first-order wide bandpass active filter for communication systems. In this study, a tunable filter with adjustable bandwidths from 100 Hz to 2 MHz and a broad frequency range of 1 kHz to 10 MHz was successfully designed simulated prototyped and tested. Applications like Software-Defined Radio (SDR) RF communication and signal processing can benefit from the filters steady performance low noise and minimal distortion. While real-time tunability was made possible by the use of variable resistors and capacitors the frequency response of the filter could be precisely controlled through the use of active components like operational amplifiers. Finally for communication systems that need flexible frequency adjustment the tunable first-order wide bandpass active filter created in this study provides an affordable and useful solution. The performance of tunable filters in sophisticated communication applications could be further enhanced by future research into the creation of higher-order tunable filters with better selectivity and sharper frequency roll-offs.

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