

A Fully Balanced Bandpass Filter and Its Application

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ABSTRACT

This article presents a fully balanced bandpass filter (BPF) with improved linearity and temperature stability. The initial design uses a symmetric six-NPN structure with a pole frequency tunable via bias current, but it suffers from high temperature sensitivity and harmonic distortion. To address this, a second circuit applies the CAPRIO technique to decouple the pole frequency from the temperature-dependent transconductance. This topology, with four NPN transistors, three resistors, and two capacitors, greatly reduces thermal effects on pole frequency and lowers distortion. Simulations show that the CAPRIO-based BPF achieves 0.562% total harmonic distortion and strong manufacturing robustness with a Monte Carlo coefficient of variation of 5.99%. Its successful use in a sinusoidal oscillator demonstrates its suitability for high-fidelity, temperature-stable analog signal processing.

Keywords: Fully Balanced, Bandpass Filter, Temperature Sensitivity, CAPRIO, Oscillator

1. INTRODUCTION

Analog filters are fundamental components of hardware, fulfilling vital functions in applications such as control systems, measuring instruments, and electronics [1, 2]. The development of versatile circuits, like the fully differential universal filter [1], is essential for modern integrated systems to realize multiple filter responses within a single structure. Stringent modern requirements

often necessitate optimal design methodologies, such as employing particle swarm optimization [3]. While RLC passive filters were historically common [4, 5], their bulky inductors restrict miniaturization. Consequently, active filters using resistors, capacitors, and transistors have become the standard, offering greater flexibility and electronic tunability within a smaller footprint.

Bandpass filters (BPFs) are critical in wireless receivers to isolate channels and block noise. Recent research shows a trend toward using the CDBA in both voltage-mode [6] and current-mode [7] configurations for high-Q designs with minimal components. Other implementations utilize operational amplifiers (op-amps) [8, 11] or operational transconductance amplifiers (OTAs) [9, 10] to achieve adjustable pole frequencies. Furthermore, electronically controllable BPFs have been presented using Controlled Current Conveyors (CCCII/CCCFA) [12–14], digitally adjustable current amplifiers (DACA) [15], single CC-CDBA configurations [16], and CMOS active inductors for RF applications [17].

Recently, the CAPRIO technique has been applied to enhance the performance of integrators [18, 19], low-pass [20, 21], high-pass [22], and all-pass filters [23]. These works demonstrate the technique's ability to mitigate harmonic distortion and improve linearity. However, while these previous studies focused on first-order or integrator structures, this work proposes the first fully balanced second-order BPF topology that explicitly decouples the pole frequency from temperature-dependent transconductance. The transition towards fully balanced differential circuits is a major trend in analog design, essential for high-frequency RF amplifiers [24] and core analog blocks [25, 26]. The inherent advantages of this architecture include superior common-mode noise rejection and improved dynamic range. Parallely, research into temperature-insensitive components, such as floating simulators [27, 28] and capacitance multipliers [29, 30], has addressed the critical need for stability in active circuits against the temperature dependency of BJTs and MOSFETs [31–34].

BJT technology is selected for its superior transconductance to current ratio and precise exponential characteristics, which are ideal for current-tunable active filters. However, the proposed architecture and CAPRIO technique can also be adapted to CMOS by operating MOSFETs in the subthreshold region or to BiCMOS. This adaptability allows for integration into modern mixed-signal SoCs, significantly reducing power consumption

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and silicon area.

2. MATERIALS AND METHODS

The proposed circuits in Figs. 1 and 2 are designed using a fully balanced architecture, featuring differential input signals (V_{in+} , V_{in-}) and differential output signals (V_{out+} , V_{out-}). To provide a rigorous mathematical analysis, the transfer functions derived in Equations (1) and (7) specifically refer to differential-mode signals. These variables are explicitly defined as $V_{in} = V_{in+} - V_{in-}$ and $V_{out} = V_{out+} - V_{out-}$, ensuring high common-mode rejection and improved dynamic range.

The proposed circuit in Fig. 1 is the fully balanced band-pass filter, which is simply designed. This configuration, employing bipolar junction transistors (BJTs), is a common structure for high-frequency active filters. The proposed circuit structure is minimally compact due to the use of six matched NPN transistors, two capacitors, and two current sources. The small differential input voltage signal is transmitted to the base pins of two differential pair transistors, Q_1 and Q_2 . Across capacitor C_1 , the output voltage is measured. Equation (1) can be used to analyze and articulate the voltage transfer function of a fully balanced band-pass filter in Fig. 1.

$$\frac{V_{in}(s)}{V_{out}(s)} = \frac{8sCr_e}{16s^2C^2r_e^2 + 8sCr_e + 1} \quad (1)$$

To simplify the transfer function analysis in Equations (1) and (6), it is assumed that the two capacitors are equal, such that $C_1 = 2C_2 = C$. Equation (2) explained that r_e is the small-signal emitter resistance of the transistor and can be adjusted by the control DC bias current (I_f), with V_T being the thermal voltage. (At room temperature, it is 26 mV.)

$$r_e = \frac{V_T}{I_f}. \quad (2)$$

From Equation (1), it is possible to analyze the pole frequency (ω_p) as follows:

$$\omega_p = \frac{1}{4Cr_e}. \quad (3)$$

When replacing the r_e of Equation (2) with the obtained pole frequency and substituting the circuit's parameters, where r_e is derived from the transistor's small-signal resistance, it yields:

$$\omega_p = \frac{I_f}{4CV_T}. \quad (4)$$

Equation (4) indicates that the pole frequency can be electronically controlled by adjusting the DC bias current. Additionally, it can be tuned by changing the capacitor. For the proposed second-order bandpass filter, the quality factor (Q) is a crucial parameter defining the selectivity of the filter. Based on the derived transfer

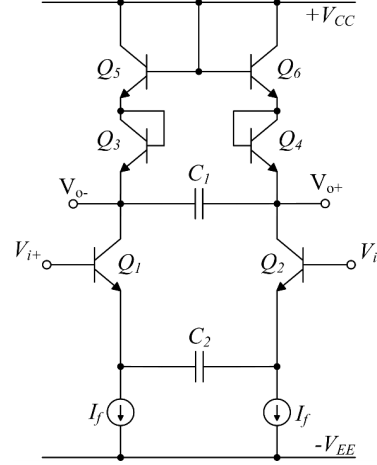


Fig. 1: The fully balanced band-pass filter.

functions, the theoretical expression for the Q-factor of the circuits can be expressed as Equation (5):

$$Q = \frac{2Cr_e}{4Cr_e} = 0.5. \quad (5)$$

As observed from Equations (3) and (5), a notable limitation of this proposed circuit is that the pole frequency and the quality factor cannot be tuned independently. Since both parameters are functions of the identical passive components and the bias current (I_f), any adjustment to the pole frequency will inherently alter the quality factor. This feature of current-controlled tunability is a key advantage of active BJT-based filter circuits. Equation (6) represents the sensitivities of the active and passive elements of the band-pass filter shown in Fig. 1.

$$S_C^{\omega_p}, S_{V_T}^{\omega_p} = -1, S_{I_f}^{\omega_p} = 1. \quad (6)$$

Other than that, the magnitudes of the active and passive sensitivity are equal to one. The sum is that the pole frequency and phase response can be adjusted through the current bias I_f and the capacitor. However, a notable limitation of this circuit is that the pole frequency and the quality factor cannot be tuned independently. Since both parameters are functions of the same passive components (R and C) and the bias current, adjusting the pole frequency will inherently affect the value of the quality factor.

The proposed circuit in Fig. 2 adapts the band-pass filter in Fig. 1 to reduce temperature sensitivity by using a resistor and overall harmonic distortion using the CAPRIO method.

The circuit presented in Fig. 2 has four matched NPN transistors, two capacitors, three resistors, and two current sinks. The input signal voltage bias at the base pin of the pair of transistors Q_1 and Q_2 and the transistors Q_3 and Q_4 in this part increases in the circuit to cancel the r_e of the transistor. Specifically, the circuit uses the transconductance characteristics of Q_3 and Q_4 to linearize the differential pair (Q_1 and Q_2), effectively

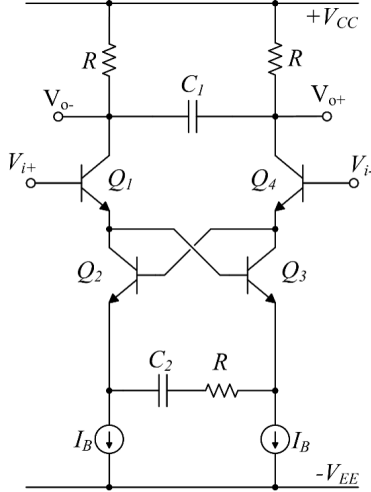


Fig. 2: The fully balanced band-pass filter was designed with the CAPRIO technique.

implementing the CAPRIO technique. It is the CAPRIO technique to reduce the total harmonic distortion of the circuit. The output voltage is taken across the capacitor (C_1). The resistors are used to replace the r_e of the transistors to reduce the effect of temperature on the transistor. This critical switch ensures that the pole frequency is primarily determined by the passive component. Equation (7) analyzes the voltage transfer function of the enhanced circuit in Fig. 2.

$$\frac{V_{in}(s)}{V_{out}(s)} = \frac{4sCR}{4s^2C^2R^2 + 4sCR + 1}. \quad (7)$$

From Equation (8), the pole frequency can be analyzed as follows:

$$\omega_p = \frac{1}{2CR}. \quad (8)$$

Equation (8) shows that the pole frequency depends solely on the passive component. The Q-factor of the circuit can be expressed as Equation (9):

$$Q = \frac{CR}{2CR} = 0.5. \quad (9)$$

Equation (9) indicates that the quality factor of the improved BPF with the CAPRIO technique is also governed by the same passive components that determine the pole frequency in Equation (8). Consequently, the orthogonal (independent) tuning of the pole frequency and Q is not achievable in either of the proposed designs. This confirms the target of temperature insensitivity. The sensitivities of the active and passive components of the circuit are represented by the equation

$$S_C^{\omega_p}, S_R^{\omega_p} = -1. \quad (10)$$

In summary, the pole frequency of the circuit depicted in Fig. 2 is determined by its passive resistors and capacitors. As demonstrated by the sensitivity analysis in Equation (10), this design exhibits excellent temperature

stability because the CAPRIO technique effectively cancels the thermal voltage dependence of the transistors. Consequently, the proposed design functions as a highly temperature-insensitive fully balanced bandpass filter. Although it trades off the electronic current-tunability of the first circuit, the substantial improvements in linearity and thermal stability make it highly suitable for high-fidelity applications.

3. RESULTS AND DISCUSSION

The PSpice simulation program was used to evaluate the workings and theoretical validity of the proposed circuits. AT&T's NR200N NPN transistor model parameters are utilized in the simulation. The band-pass filter shown in Fig. 1 is constructed with $C_1 = 0.1$ nF, $C_2 = 0.2$ nF, and $I_f = 50\mu$ A; the band-pass filter in Fig. 2 is built with $R = 1,040\Omega$, $C_1 = 0.1$ nF, $C_2 = 0.2$ nF, $I_B = 50\mu$ A, and both circuits use a supply voltage of ± 2 V.

Based on the simulation results illustrated in Fig. 3, the fully balanced band-pass filter (Unimproved BPF) in Fig. 1 has a pole frequency of approximately 749.89 kHz, and the fully balanced band-pass filter designed with the CAPRIO technique (Improved BPF) in Fig. 2 has a pole frequency of approximately 741.31 kHz, with both circuits having a voltage gain of approximately 0 dB. Using equation 4, it was determined that the simulation pole frequency differed from the theoretical value of 765.65 kHz by approximately 2.05 percent and 3.17 percent, respectively.

Fig. 4 illustrates the gain responses of the band-pass filter circuits under various capacitor configurations: $C_1 = 0.1$ nF, $C_2 = 0.2$ nF; $C_1 = 0.2$ nF, $C_2 = 0.4$ nF; $C_1 = 0.4$ nF, and $C_2 = 0.8$ nF. The pole frequencies of the unimproved BPF shift to 749.89 kHz, 375.837 kHz, and 187.5 kHz, respectively, which aligns with the theoretical values calculated from Equation (4). Similarly, the pole frequencies of the improved BPF shift to 741.31 kHz, 370.681 kHz, and 185.353 kHz, showing consistency with Equation (8). The results demonstrate an inverse relationship between the capacitance and the pole frequency, as expected from the design equations.

The temperature simulations shown in Figs. 5 and 6 utilized passive components (resistors and capacitors) modeled as ideal elements with a zero temperature coefficient. This approach was deliberately chosen to isolate the thermal behavior of the active BJT devices from the passive network.

The impact of temperature variations on both the unimproved and improved BPF configurations is illustrated in Figs. 5 and 6, respectively. Both circuits were evaluated across a temperature range of 0°C , 25°C , 50°C , and 100°C . The pole frequencies of the unimproved BPF shifted to 822.243 kHz, 755.092 kHz, 698.232 kHz, and 605.341 kHz, respectively, whereas the pole frequency of the improved BPF remained stable at 741.31 kHz. This significant disparity in sensitivity represents a key finding: the frequency of the unimproved BPF fluctuates because its pole frequency is inherently dependent on

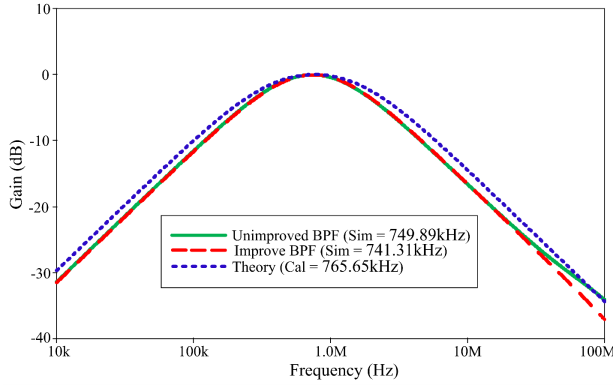


Fig. 3: The gain responses of unimproved and improved BPF at pole frequency.

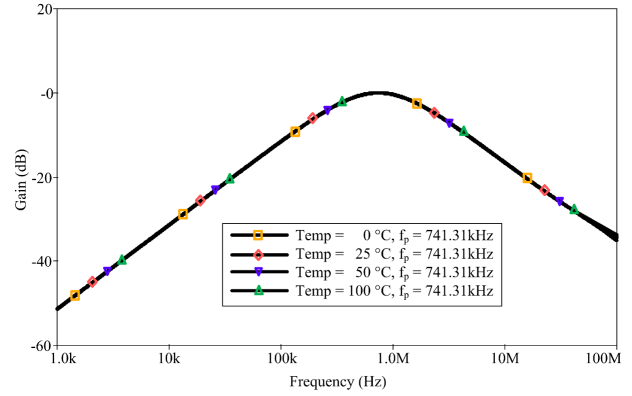


Fig. 6: Changes in temperature affect the pole frequency of improved BPF.

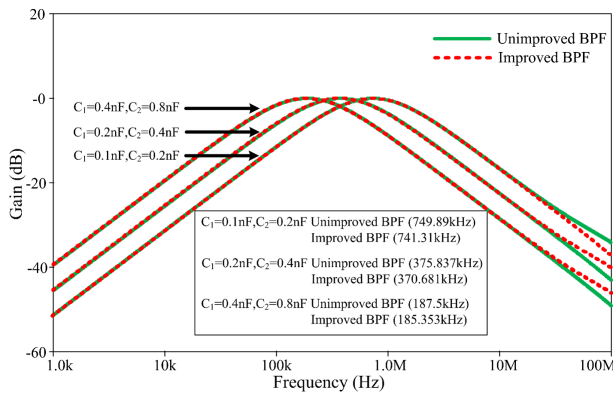


Fig. 4: Changes in capacitor values of C_1 and C_2 affect the pole frequency of unimproved and improved BPF.

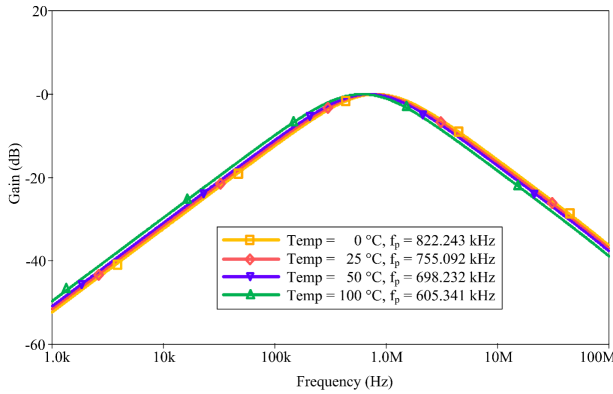


Fig. 5: Changes in temperature affect the pole frequency of unimproved BPF.

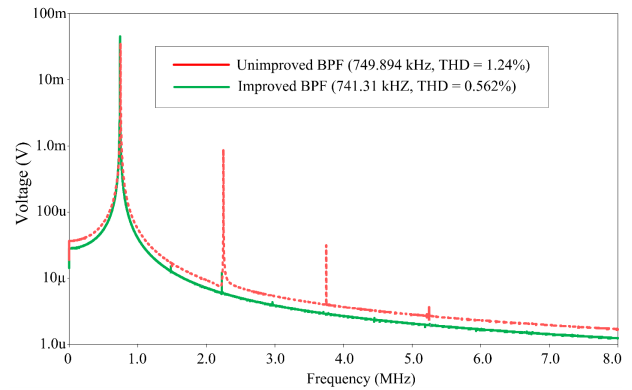


Fig. 7: The total harmonic distortion of both circuits.

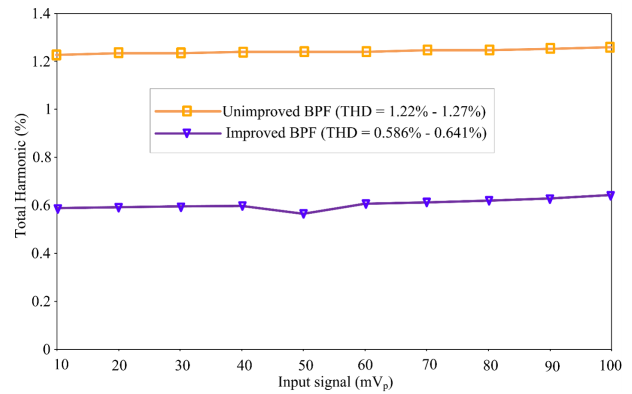


Fig. 8: The THD characteristics of unimproved and improved BPF.

the temperature-sensitive intrinsic of the transistor's small-signal resistance. Consequently, the unimproved BPF frequency exhibits a substantial temperature drift of approximately 26.38% over the tested range, further validating the necessity of the CAPRIO-based enhancement in the improved BPF design.

Fig. 7 compares the THD of both BPF configurations at an input amplitude of $0.05 V_p$. Under identical testing conditions at their respective pole frequencies,

the unimproved BPF exhibits a THD of 1.24%, whereas the improved CAPRIO-based BPF significantly reduces this distortion to 0.562%.

Fig. 8 compares the THD performance of both BPF configurations across an input range of $0.01 V_p$ to $0.1 V_p$ at their respective pole frequencies. For the unimproved BPF, the THD remains high (1.22%–1.27%) due to the inherent non-linearity of the BJT differential pair. In contrast, the CAPRIO-based BPF significantly enhances linearity, maintaining a much lower THD

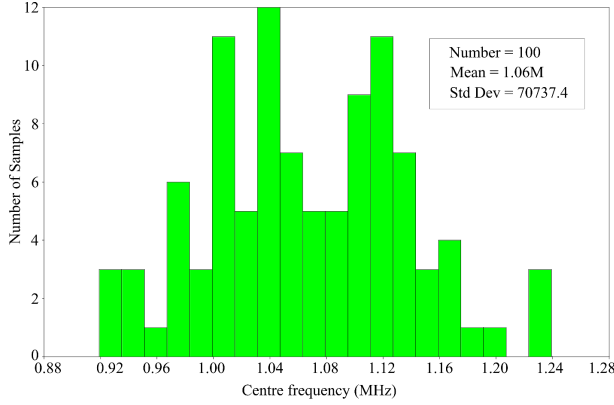


Fig. 9: Statistical distribution of center frequency for the unimproved BPF.

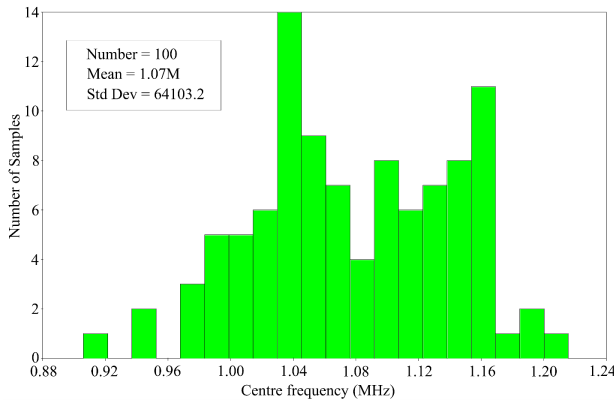


Fig. 10: Statistical distribution of center frequency for the improved BPF.

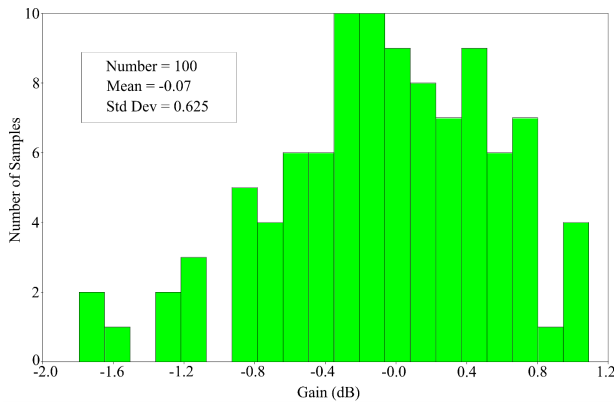


Fig. 11: Statistical distribution of gain for the unimproved BPF.

between 0.586% and 0.641%.

Furthermore, the performance of the filters was evaluated based on their power consumption and selectivity. The total power consumption of the unimproved BPF was measured at 0.797 mW, while the improved CAPRIO-based BPF exhibited a significantly lower power consumption of only 0.398 mW under a ± 2 V supply. This represents a 50% reduction in power

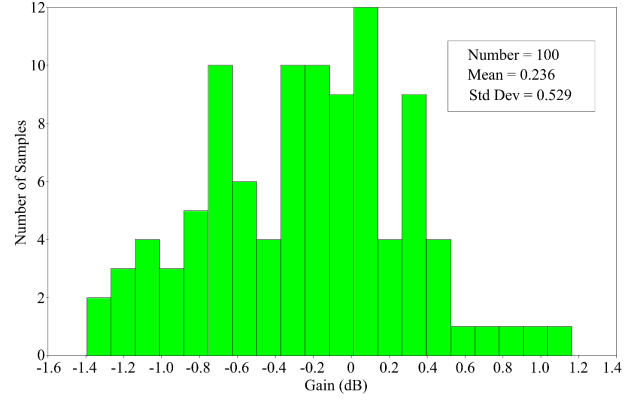


Fig. 12: Statistical distribution of gain for the improved BPF.

usage, further highlighting the efficiency of the CAPRIO technique. Additionally, the bandwidths of the proposed circuits were measured to evaluate their selectivity. By extracting the parameters directly from the simulated frequency responses, the bandwidth of the unimproved BPF was found to be 1,482.81 kHz, which corresponds to a simulated quality factor (Q) of 0.51. Similarly, the improved BPF maintained a nearly identical bandwidth of 1,482.80 kHz, resulting in a simulated Q of 0.50. These extracted simulated Q values are highly consistent with the theoretical expectations ($Q \approx 0.5$) derived in the mathematical analysis.

It is worth noting that the theoretical and simulated quality factors indicate a relatively low value ($Q \approx 0.5$), implying a wide bandwidth and low selectivity. Although this low- Q characteristic might not be suitable for narrow-band channel selection, it is highly advantageous for specific practical applications. For instance, such low- Q bandpass filters are well-suited for wideband signal conditioning, where maintaining phase linearity and minimal signal distortion over a broad frequency range is essential. Furthermore, as will be demonstrated in the subsequent section, this filter is highly applicable to oscillator-related applications, where it effectively serves as a frequency-determining network to generate stable sinusoidal waveforms.

Fig. 13 illustrates the architecture of a sinusoidal oscillator designed using the proposed improved BPF from Fig. 2. By cascading the filter with a unity-gain amplifier, a second-order feedback network is formed (Fig. 8), representing a fundamental approach to sinusoidal signal generation in Fig. 14. To ensure stable oscillation, the circuit satisfies the Barkhausen stability criterion, requiring a loop gain of unity and a total phase shift of 0 or $2n\pi$ at the oscillation frequency.

The corresponding voltage transfer function of the oscillator is expressed in equation (11).

$$s^2 + \frac{1}{sCR_f}(1-k) + \frac{1}{4C^2R_f^2} = 0. \quad (11)$$

The oscillator circuit will produce sinusoidal signals if

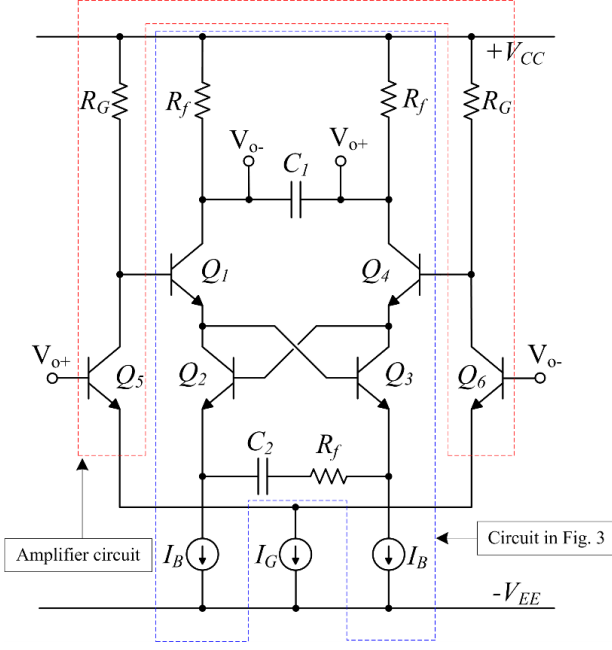


Fig. 13: Oscillator with band pass filter.

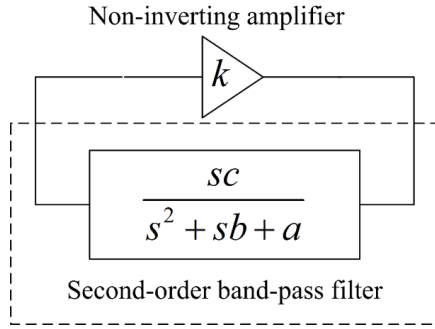


Fig. 14: A sinusoidal oscillator with a second-order band-pass filter feed-back network [35].

the condition of oscillation (CO) is configured as follows:

$$1 - k \cong 0. \quad (12)$$

When $k = \frac{R_G}{r_e}$ and $r_e = \frac{2V_T}{I_G}$. The frequency of oscillation (FO) of the proposed sinusoidal oscillator can be calculated as follows:

$$\omega_p = \sqrt{\frac{1}{4C^2R^2}}. \quad (13)$$

It was found that the CO and the FO can be adjusted independently. The CO can be adjusted electronically (I_G) without affecting the frequency, and the FO can be adjusted by passive equipment (R_f and C_{1-2}). This crucial feature of independent control (where R_G is related to I_G via transistor characteristics, and the frequency is determined by the stable passive components) is highly desirable in practical oscillator design.

The proposed sinusoidal oscillator in Fig. 13 is implemented by setting the voltage supply to ± 2 V and

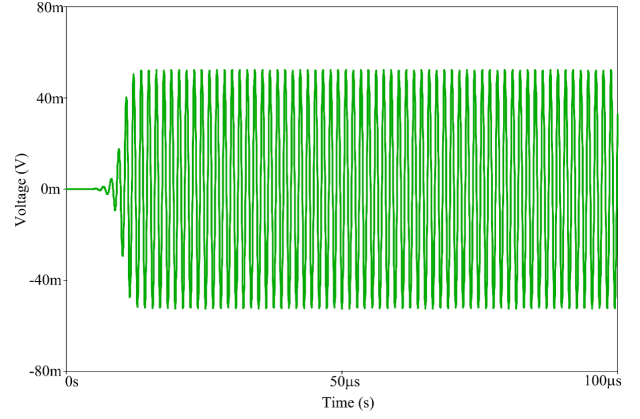


Fig. 15: Transient state of sinusoidal signal.

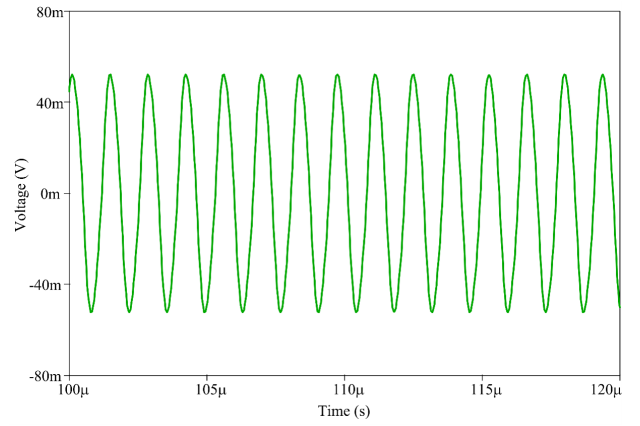


Fig. 16: Steady state of sinusoidal signal.

the bias current to $I_B = 50\mu A$. Also, the passive elements were designated as $R_f = 1,040, \Omega$, $C_1 = 0.1$ nF, and $C_2 = 0.2$ nF. The condition of oscillation is set to $R_G = 1,300, \Omega$ and $I_G = 50\mu A$ following equation 10. The frequency of oscillation was 730 kHz, which deviated from the theoretical figure (765.16 kHz) by about 4.59%. The results in Fig. 15 show the transient state of the sine signal at times between 0 and 100 microseconds, and the results in Fig. 16 show the steady state of the sine signal at 100 microseconds. Both figures confirm the operation of the designed circuit and that Equation 13 is correct.

Table 1 presents a performance comparison between the proposed bandpass filter (BPF) and other state-of-the-art designs, highlighting that the proposed CAPRIO-improved BPF effectively eliminates temperature sensitivity (reducing a 26.38% drift to a stable level) and significantly lowers the Total Harmonic Distortion (THD) to just 0.562% while consuming only 0.398 mW. Although other CMOS-based designs consume significantly less power because they are tailored for ultra-low-frequency biomedical applications (e.g., 10 Hz and 303.5 Hz), the proposed fully balanced BJT architecture stands out for its high linearity, reliable robustness (MC CV of 5.99%), and excellent thermal stability.

Furthermore, to comprehensively evaluate the filter's

Table 1: Comparison of the proposed BPF with other state-of-the-art designs.

Reference	Technology	Topology	Supply Voltage	Power	Center Freq.	THD (%)	Dynamic Range	FoM (10^{-18} J)	Temp. Sensitivity	Robustness (MC CV)	Tuning Method	Application
[1]	0.18 μ m CMOS	Fully Diff. (MI-OTA)	0.5 V	53.3 nW	10 Hz	0.33%	63 dB	1.34	Low	Gain std. dev. = 2.96 m dB	Elec.	Bio-signal / Universal Filter
[16]	0.18 / 0.35 μ m CMOS	Fully Diff. / Single-Ended (MO-CF,ACA)	± 1.2 V	-	1 MHz	-	-	-	-	-	Elec.	BPF
[17]	BJT	Single-Ended (CC-CDBA)	± 2.5 V	-	123.4 kHz - 246.7 kHz	-	-	-	-	-	Elec.	BPF
[18]	0.35 μ m CMOS	Active Inductor (MOSFET)	2.7 V	45.9 mW	900 MHz	-	SFDR 28 dB	-	-	-	Elec.	RF / Wireless
[36]	0.35 μ m CMOS	Flipped Voltage Follower	0.8 V	2 nW	303.5 Hz	1.11%	58 dB	4.04	Simulated (PVT corners)	3.05%	Elec.	Bio-medical
Proposed Unimproved	BJT	Fully Balanced	± 2 V	0.797 mW	749.89 kHz	1.24%	-	-	High (26.38% drift)	6.67%	Elec.	BPF
Proposed Improved	BJT	Fully Balanced	± 2 V	0.398 mW	741.31 kHz	0.562%	65.55	74.7	Negligible (Stable)	5.99%	Passive	BPF / Osc.

performance, the dynamic range (DR) and Figure-of-Merit (FoM) were determined. Based on the noise analysis, the input-referred noise was found to be 0.0526 mV_{rms}. With a maximum input signal of 99.70 mV_{rms} (measured at 1% THD), the proposed improved BPF achieves a wide dynamic range of 65.55 dB. Consequently, using the standard equation:

$$FoM = \frac{P}{N \times f_C \times DR}, \quad (14)$$

where P is power consumption of the improved BPF, N is the order of the improved BPF, and the calculated FoM is 74.7×10^{-18} J (or 74.7 aJ). As compared in Table 1, while the proposed BJT-based circuit naturally consumes more power compared to ultra-low-frequency subthreshold CMOS designs, it provides a competitive FoM by demonstrating a significant improvement in linearity (0.562% THD), a wide dynamic range, and robust thermal stability at a much higher operating frequency (741.31 kHz).

4. CONCLUSIONS

This article presents the design and development of a fully balanced bandpass filter (BPF) circuit. The first proposed circuit achieves frequency tunability through electronic control of the bias current. However, its operation is significantly affected by the temperature dependency of the BJT properties, exhibiting a large frequency drift of approximately 26.38% over a 100°C range. To address this weakness, the second circuit introduces the first fully balanced BPF employing the CAPRIO linearization technique. This improved design successfully eliminates the temperature-dependent transconductance from the pole frequency, resulting in excellent thermal

stability. Furthermore, the CAPRIO technique achieves a significant reduction in total harmonic distortion (THD) from 1.24% down to 0.562% while consuming only 0.398 mW. The robustness of the proposed circuit was also verified through Monte Carlo mismatch analysis, demonstrating a highly reliable coefficient of variation (CV) of 5.99% for the pole frequency. Compared to recent state-of-the-art designs, the proposed filter offers competitive performance in terms of linearity, power consumption, and thermal stability.

Lastly, a sinusoidal oscillator based on the improved BPF was demonstrated as a practical application to validate its functionality. All presented circuits yield PSpice simulation results that are highly consistent with theoretical analysis. Although currently implemented using BJT technology, the proposed fully balanced architecture and CAPRIO technique can be effectively adapted to CMOS technology (e.g., operating in the subthreshold region), making it highly relevant for modern mixed-signal IC integration. Future work will focus on experimental validation through hardware prototyping, such as IC fabrication or PCB measurements, and extending the technique to a wider frequency range.

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AUTHOR CONTRIBUTIONS

The individual contributions of the authors are specified as follows:

Conceptualization, Methodology, Software (PSpice Simulation), Formal Analysis, Writing – Original Draft Preparation: Yotaka Tungtragul and Atirarj Suksawad.

Investigation (Literature Review), Validation (Theoretical Analysis): Suttipong Fungdetch, Nuttapong Boothanu, Data Curation (Processing simulation results), Writing – Review & Editing: Suttipong Fungdetch, Nuttapong Boothanu, and Chai Wankan.

Project Administration, Supervision, Resources, Writing – Review & Editing, Funding Acquisition: Chayada Surawanitkun and Atirarj Suksawad.

All authors reviewed and approved the final version of the manuscript.

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