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THE DEVELOPMENT OF A 10.7-MHz FULLY BALANCED CURRENT-TUNABLE BANDPASS FILTER WITH CAPRIO TECHNIQUE

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Abstract

Bandpass filters are integral in modern communication systems for selecting specific frequency ranges to ensure interference-free signal transmission and reception. This paper explores various bandpass filter designs, including those using active inductors, transmission-line unit-cells, microstrip open-loop resonators, and dual-port dual-frequency integration antennas. The focus is on the 10.7-MHz bandpass filter, widely used in FM radio and television systems. The study evaluates current-controlled and balanced designs, analyzing their performance, advantages, and drawbacks. Unique trade-offs in terms of linearity, distortion, temperature sensitivity, and component variations are discussed. Additionally, advancements in filter technology and diverse design options are presented. The paper introduces a novel current-balanced, frequency-adjusted bandpass filter to address odd-order noise issues. This filter aims to achieve high linearity, harmonic distortion attenuation, and the elimination of even-order harmonics. Through synthesis, analysis, simulation, and comparison with traditional filters, the proposed design enhances signal quality and efficiency. The fully-balanced current-tunable bandpass filter with the Caprio technique at 10.7 MHz is developed, exhibiting symmetrical characteristics with lower total harmonic distortion. The circuit's structure is simple and adaptable for integration, validated through consistent simulation results. The study concludes by emphasizing the constant sensitivity of transistor differential amplifier circuits to the center frequency and the linear relationship between center frequency and adjustable bias current. The suggested transistor and capacitor selection criteria contribute to optimizing the circuit's performance, aligning with the Caprio technique's recommendations. Overall, this research presents a promising solution for achieving high-quality signal transmission in contemporary communication systems.

Keywords: 10.7-MHz bandpass filter, fully balanced, current-tunable, sensitivities, harmonic distortion, Caprio technique.

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1. Introduction

Bandpass filters play a pivotal role in modern communication systems, enabling the selection of specific frequency ranges from a broader spectrum to facilitate interference-free signal transmission and reception. Researchers have explored a variety of bandpass filter designs using diverse materials and techniques. For instance, [1] introduced an approach utilizing an active inductor to create a tunable bandpass filter with floating dual resistor feedback. Meanwhile, [2] proposed an ultra-wideband bandpass filter based on a transmission-line unit-cell incorporating composite right/left-handed elements. In a similar vein, [3] introduced a novel dual-mode bandpass filter, harnessing the characteristics of a microstrip open-loop resonator to achieve a broad stopband. Additionally, [4, 5] focused on the development of a dual-port dual-frequency integration antenna, while [6] addressed the specific needs of implantable defibrillators and defibrillators by designing bandpass filters for NIR charging. The 10.7-MHz bandpass filter, which originated from the intermediate frequency stage of a superheterodyne receiver and is commonly used in FM radio and television systems, has undergone extensive research [7–11]. The relevance of the 10.7-MHz bandpass filter design is emphasized in [10], which presents a High-Q bandpass filter boasting an impressive 87 dB dynamic range at the same frequency. In the domain of bandpass filter designs, various current-controlled and balanced designs have been explored, as evident in [12–14]. In this evaluation, let's meticulously assess their performance, advantages, and drawbacks, offering a critical analysis of their potential applications. However, each design presents its unique trade-offs. For instance, [12] enhances linearity and minimizes distortion but demands a complex design and may be sensitive to temperature variations. In contrast, [13] optimizes bandwidth and stability but may be more susceptible to component variations. Meanwhile, [13] offers improved selectivity and tuning range but may entail greater complexity and cost. Further advances in filter technology and diverse design options for various applications are presented in [15–30]. While [15–19] emphasize enhanced selectivity and bandwidth, they may exhibit sensitivity to temperature and fabrication variations. [20] prioritizes improved linearity and stability but may necessitate the incorporation of multiple tuning elements. [21] introduces a low-distortion Bessel filter designed for a specific frequency, and [22] proposes a low-distortion transconductor bandpass filter tailored for intermediate frequency (f_c) applications. [23] delves into the design of a high-frequency current mode oscillator using the f_T integration technique, while [24] unveils a downconverter/AGC IC for digital audio broadcasting based on a Si BJT. Finally, [25] outlines the concept of a High-Q tuned active bandpass filter designed for wireless applications, and [26] presents their work on Mixed-mode Multiphase Sinusoidal Oscillators using Differential Voltage Current Conveyor Transconductance Amplifiers and Only Grounded Passive Components. A review of the relevant literature reveals that the issue of odd-order noise in circuits, caused by limited gain and harmonic distortion, has not been resolved.

In a broader context, the paper primarily focuses on addressing the issue of odd-order noise in circuits, often attributed to gain and limited harmonic distortion [12, 19]. To mitigate these challenges and achieve high linearity, harmonic distortion attenuation, and the elimination of even-order harmonics, the paper introduces a current-balanced, frequency-adjusted bandpass filter. This filter undergoes a comprehensive process involving synthesis, analysis, simulation, and a detailed comparison with traditional bandpass filters [27]. By incorporating this innovative filter, the proposed circuit design significantly enhances overall quality and efficiency. The utilization of current balancing and frequency adjustment effectively removes unwanted harmonics and noise from the signal. This synthesis, analysis, and simulation process ensures the filter is precisely optimized to meet specific circuit requirements. Furthermore, the comparison with conventional bandpass filters validates the effectiveness of the proposed filter design. Overall, this innovative design offers a promising solution for achieving high-quality signal transmission and reception in modern communication systems.

The research introduces the development and design of a fully-balanced current-tunable bandpass filter using the Caprio technique. The objectives of this study are as follows:

– to develop and design a 10.7-MHz fully-balanced current-tunable bandpass filter with Caprio technique;

– to compare the performance of the developed circuit with the theoretical design of a 10.7 MHz fully-balanced current-tunable bandpass filter with Caprio technique through simulation using PSpice.

2. Materials and methods

2. 1. Circuit description and ideal analysis

Fig. 1, depicts the circuit of a fully balanced current-tunable bandpass filter as proposed in [27]. The circuit includes four identical NPN transistors, two capacitors designated as C_1 and C_2, and an adjustment circuit. Additionally, it features two bias currents (I_f).

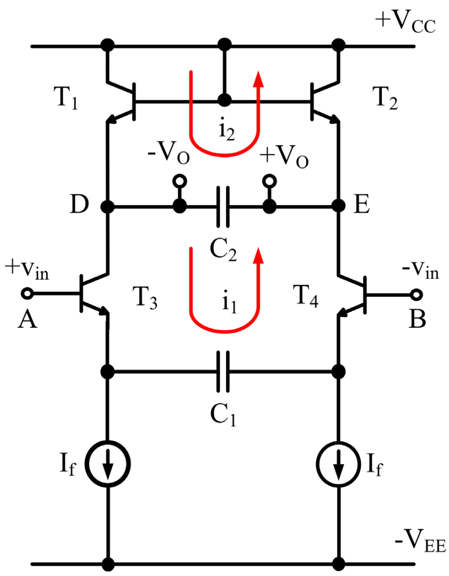

Fig. 1. A fully balanced current-tunable bandpass filter

From **Fig. 1**, it can be observed that within the structure of the NPN transistor, the resistance of the diode or PN junction during forward biasing is:

$$r_e = \frac{V_T}{I_f}, \tag{1}$$

where V_T is the thermal voltage, equal to kT/q, and k is the Boltzmann constant. «T» Represents the absolute junction temperature, and q is the charge per electron, V_T is approximately 26 mV at 25 °C, and I_f is the diode bias current. From equation (1), it can be seen that the value of r_e is inversely proportional to the value of I_f. Thus, in a fully balanced current-tunable bandpass filter, as shown in **Fig. 1**, the circuit can be analyzed by assigning transistors T_1 to T_4 with exactly the same characteristics and β values. The input signal is fed to nodes A and B, and the output signals are taken from nodes D and E, respectively. This allows to write equation i_1:

$$i_1 = v_{in}\frac{sC_1}{(1+sC_1 2r_e)}. \tag{2}$$

And the current i_2 at nodes D and E, or the emitter terminals of transistors T_1 and T_2, is equal to (3):

$$i_2 = v_{in}\frac{i_1}{(1+sC_2 2r_e)}. \tag{3}$$

So, let's obtain the differential output voltage «v_o», which is equal to (4):

$$\frac{v_o}{v_{in}} = \frac{sC_1 2r_e}{(1+sC_1 2r_e)(1+sC_2 2r_e)}. \tag{4}$$

It can be seen that equation (4) qualifies as a bandpass filter transfer function. So, when $C_1 = C_2 = C$ and $\tau = 2r_e C$, we get equation (5):

$$\frac{v_o}{v_{in}} = \frac{\left(\frac{1}{\tau}\right)s}{s^2 + \left(\frac{2}{\tau}\right)s + \frac{1}{\tau^2}}. \tag{5}$$

From equation (5), it is possible to calculate the center frequency (ω_0) of a bandpass filter using equation (6):

$$\omega_0 = \frac{1}{\tau} = \frac{I_f}{(2V_T C)}. \quad (6)$$

In equation (6), the center frequency (ω_0) can be tuned by adjusting the current I_f and changing the capacitor value (C). A bandpass filter shown in **Fig. 1**, is actually applied in the reference [28].

However, for the bandpass filter shown in **Fig. 1**, the center frequency (ω_0) is affected by changes in temperature, as depicted in equation (6). Additionally, the filter exhibits relatively high total harmonic distortion (THD). Based on the issues mentioned above, the researcher has improved and developed the bandpass filter shown in **Fig. 1,** by using the Caprio technique [6, 15]. **Fig. 2,** shows the circuit obtained by applying the Caprio technique to improve the circuit shown in **Fig. 1**. A10.7-MHz fully balanced current-tunable bandpass filter using the Caprio technique is shown in **Fig. 2**.

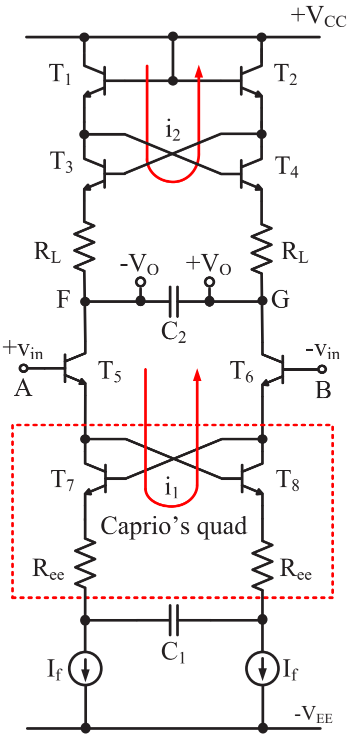

Fig. 2. A 10.7-MHz fully balanced current-tunable bandpass filter with Caprio technique

The circuit comprises ten identical NPN junction transistors (BJTs) (T_1 to T_8) connected to two capacitors (C_1 and C_2), four resistors ($2R_{ee}$ and $2R_L$ where R_{ee} and R_L have equal value), and one bias currents (I_f). The center frequency (ω_0) of a fully balanced current-tunable bandpass filter using the Caprio technique, shown in **Fig. 2**, is re-analyzed in equation (7):

$$i_1 = v_{in} \frac{sC_1}{[1 + sC_1(4r_e + 2R_{ee})]}. \quad (7)$$

And the current i_2 at nodes F and G is equal to (8):

$$i_2 = v_{in} \frac{i_1}{[1 + sC_2(4r_e + 2R_L)]}. \quad (8)$$

So, let's obtain the differential output voltage «v_o», which is equal to (9):

$$\frac{v_o}{v_{in}} = \frac{sC_1(4r_e + 2R_L)}{[1 + sC_1(4r_e + 2R_{ee})][1 + sC_2(4r_e + 2R_L)]}. \quad (9)$$

It can be seen that equation (9) qualifies as a bandpass filter transfer function. So, when $C_1 = C_2 = C$, $2R_L = 2R_{ee} = R$ and $\tau = (4re+R)C$ and let's obtain equation (10):

$$\frac{v_o}{v_{in}} = \frac{\left(\frac{1}{\tau}\right)s}{s^2 + \left(\frac{2}{\tau}\right)s + \frac{1}{\tau^2}}. \tag{10}$$

From equation (10), it is possible to calculate the center frequency (ω_0) of a bandpass filter using equation (11):

$$\omega_0 = \frac{1}{\tau} = \frac{I_f}{\left(4V_T + RI_f\right)C}. \tag{11}$$

In equation (11), the center frequency (ω_0) can be tuned by adjusting the current I_f and changing the capacitor value (C) and resistors (R). and equation (10), the Quality Factor (Q) of a 10.7-MHz fully balanced current-tunable bandpass filter with Caprio technique is determined from the analysis and is given by the value shown in equation (12):

$$Q = \frac{\tau}{2\tau} = 0.5. \tag{12}$$

2. 2. Caprio's Redue the even order by Volterra series

Caprio's technique emerges as a promising current-mode approach, characterized by a differential input topology featuring exceptionally low input impedance and a broad bandwidth. Employing a Volterra series analysis, it is possible to articulate the third-order intermodulation components (IM3) of the output voltage, V_{out}, at the frequency $f+2\Delta f$ as follows:

$$IM3_{Cap} \approx \left| \frac{A_{in}^2}{8g_m^3 R_{ee}^3 V_T^2} \frac{f}{f_T} \right|. \tag{13}$$

The parameters A_{in}, g_m, R_{ee}, and f_T can be acquired through the methodology outlined in references [6, 12]. The determination of IIP3 involves solving equation (14), and this can be accomplished by setting $IM3_{Cap}$ to 1, as illustrated below:

$$VII3_{Cap} \approx 2\sqrt{2V_T}\sqrt{\frac{g_m^3 R_{ee}^3 f_T}{f}}. \tag{14}$$

Here, $VIIP3_{Cap}$ denotes the third-order input-referred intercept point voltage for Caprio's Quad. This expression for $VIIP3_{Cap}$ can be streamlined as follows:

$$VII3_{Cap} \approx \sqrt{\frac{f_T I_T^3 R_{ee}^3}{f V_T}}. \tag{15}$$

«I_T» represents the total current consumption.

2. 3. Sensitivities

Sensitivities refer to alterations in the characteristics of a filter circuit when actual component values deviate from their calculated counterparts. An effectively designed filter circuit should exhibit low sensitivity, indicating that variations in component values have minimal impact on circuit characteristics. Generally, sensitivity is defined as the ratio of the change in y with respect to x, where y represents the variable of interest, and x is the variable undergoing changes.

In **Table 1**, sensitivity values are presented as $(x, y) = (\beta, Q)$, (C, ω_0), (V_T, ω_0), (I_f, ω_0), or (β, ω_0), where V_T denotes the thermal voltage. Furthermore, the temperature value also influences the center frequency (ω_0) and the quality factor (Q) [9, 10]. A well-designed filter circuit should maintain stability in the face of component variations, as reflected in its low sensitivity values.

Table 1
Sensitivity where (β, Q), (C, ω_0), (V_T, ω_0), (I_f, ω_0) or (β, ω_0)

S_{β}^{Q}	$S_{C}^{\omega_0}$	$S_{V_T}^{\omega_0}$	$S_{I_f}^{\omega_0}$	$S_{\beta}^{\omega_0}$
1.0	–1.0	–1.0	1.0	1/[2(β+1)]

3. Results and Discussion

Referring to **Fig. 2**, shown a 10.7-MHz fully balanced current-tunable bandpass filter with Caprio technique, and have also conducted simulations to validate the circuit's performance using the PSpice software [29–31]. A 10-7 MHz fully balanced current-tunable bandpass filter with Caprio technique, as illustrated in **Fig. 2**, was designed employing an NPN bipolar junction transistor (BJT) of the Q2N2222A type with an f_T of 300 MHz [32].

Fig. 3, shows the frequency response of the circuit depicted in **Fig. 2**, which is obtained by biasing the current (I_f) at 350.33 µA and using capacitors (C_1 and C_2) with a value of 150 pF, resistance value (R_{ee} and R_L) set to 10 Ω. The center frequency (f_0) has a value of 10.7 MHz and the quality factor (Q) has a value of 0.632.

Referring to **Fig. 2**, let's present a fully balanced current-tunable bandpass filter operating at 10.7 MHz, employing Caprio's technique. To validate the circuit's performance, simulations were conducted using PSpice software [31]. The design incorporates an NPN bipolar junction transistor (BJT) of the Q2N2222A type with an f_T of 300 MHz [32].

In **Fig. 3**, the frequency response of the circuit depicted in **Fig. 2** is illustrated. The current (I_f) is biased at 350.33 µA, and capacitors (C_1 and C_2) have a value of 150 pF. Resistance values (R_{ee} and R_L) are set to 10 Ω. The center frequency (f_0) is 10.7 MHz, and the quality factor (Q) is 0.632. These parameters collectively contribute to the filter's overall performance characteristics.

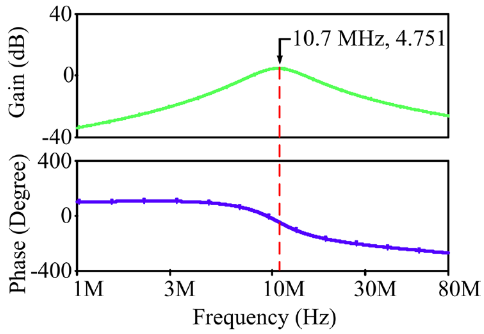

Fig. 3. Gain (dB) and phase (degree) of V_O/V_{in} at the centre frequency $f_0 = \omega_0/(2\pi) = 10.7$ MHz and quality factor $Q = 0.632$

Fig. 4, shows the center frequency (f_0) and quality factor (Q) values obtained from the analysis of the circuit depicted in **Fig. 2**, as shown in equation (11), by adjusting the bias current (I_f) and setting the capacitor (C_1 and C_2) value to 150 pF, resistance value (R_{ee} and R_L) set to 10 Ω. During the simulation of the circuit in **Fig. 2**, using the PSpice program **Fig. 4**, illustrates that the center frequency (f_0) value can be adjusted beyond level 3 while maintaining a consistent quality factor (Q) of approximately 0.5, as shown in equation (12). This quality factor remains independent of the center frequency. It is worth noting that the bias current (I_f) can be adjusted up to 50 mA.

In **Fig. 5**, the center frequency (f_0) performance of the circuit is illustrated. The analysis is based on the circuit depicted in **Fig. 2**, as described by equation (11), and simulations were conducted using the PSpice program. The bias current (I_f) is fixed at 1 mA, and resistance values (R_{ee} and R_L) are set to 10 Ω. The capacitor values (C_1 and C_2) are adjusted while maintaining a consistent quality factor (Q) of approximately 0.5. This adjustment results in the circuit's center frequency (f_0) reaching a maximum value of 138.995 MHz when the capacitor values (C_1 and C_2) are set to 1 pF.

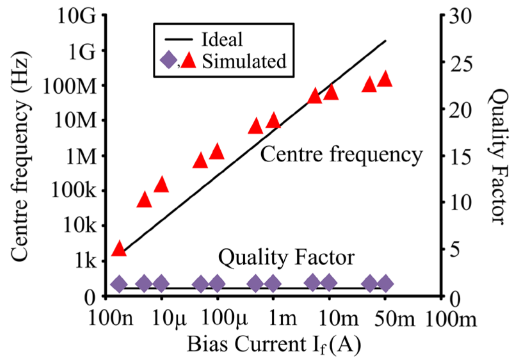

Fig. 4. Plot of the center frequency f_0 and the quality factor Q versus frequency bias currents I_f with fixed capacitance (C_1 and C_2) set to 150 pF and resistance value (R_{ee} and R_L) set to 10 Ω

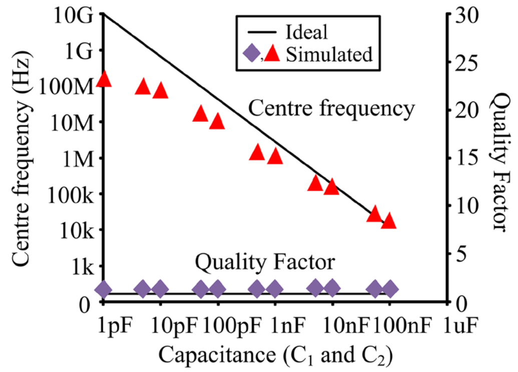

Fig. 5. Plot of the center frequency f_0 and the quality factor Q versus frequency setting capacitance (C_1 and C_2) with fixed bias currents I_f= 1 mA and resistance value (R_{ee} and R_L) set to 10 Ω

In **Fig. 6**, the center frequency (f_0) performance of the circuit is depicted. This analysis is based on the circuit illustrated in **Fig. 2**, as expressed in equation (11), and simulations were conducted using the PSpice program. The resistance values (R_{ee} and R_L) are set to a fixed bias current of I_f = 1 mA, while the capacitance values (C_1 and C_2) are set at 150 pF. Adjustments to the capacitance are made, maintaining a consistent quality factor (Q) of approximately 0.5. As a result, the circuit's center frequency (f_0) response reaches a maximum value of 29.161 MHz when the resistance values (R_{ee} and R_L) are set to 0 Ω.

In **Fig. 7**, a comparative analysis of harmonic spectral lines is presented, utilizing simulation results obtained through the PSpice program. The comparison involves a conventional fully balanced current-tunable bandpass filter, as illustrated in **Fig. 1**. This is contrasted with a recently developed 10.7-MHz fully balanced current-tunable bandpass filter utilizing the Caprio technique, depicted in **Fig. 2**. Both circuits are configured with a bias current of 1 mA, and the capacitors (C_1 and C_2) are adjusted to 150 pF. The results showcase the harmonics generated by the input frequency of 37.9 kHz. Notably, the newly developed filter exhibits a reduction in the size of the 1st, 2nd, 3rd, 4th, and 5th harmonics at the frequency values of 37.9 kHz, 75.8 kHz, 113.7 kHz, 151.6 kHz, and 189.5 kHz. This reduction is evident, leading to a notable decrease in total harmonic distortion (THD) from 2.55 % to 0.193 %.

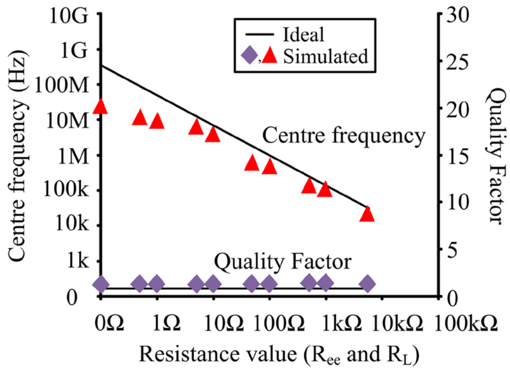

Fig. 6. Plot of the center frequency f_0 and the quality factor Q versus frequency setting resistance (R_{ee} and R_L) with fixed bias currents I_f = 1 mA and capacitance (C_1 and C_2) set to 150 pF

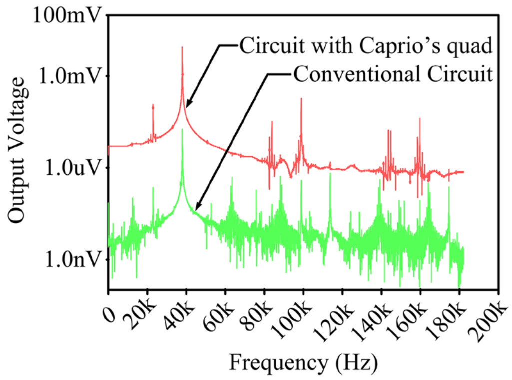

Fig. 7. Show comparison of harmonic spectral lines of A 10.7-MHz fully balanced current-tunable bandpass filter with Caprio technique

This research stands out through its targeted focus on odd-order noise, the incorporation of a unique current-balanced and frequency-adjusted design, a comprehensive comparative analysis, application in a specific frequency range, and the potential for integration into an integrated circuit. These aspects collectively contribute to the novelty and significance of the proposed bandpass filter design.

The paper introduces a novel a 10.7-MHz fully balanced current-tunable bandpass filter with Caprio technique, aiming to address the issue of odd-order noise in circuits. The uniqueness and novelty of the results, can be attributed to several key features of the proposed a 10.7-MHz fully balanced current-tunable bandpass filter with Caprio technique.

Focus on Odd-Order Noise Mitigation. The paper identifies and addresses the specific problem of odd-order noise in circuits caused by gain and limited harmonic distortion. The proposed bandpass filter is designed with the explicit goal of mitigating this issue, contributing to high linearity, harmonic distortion attenuation, and the elimination of even-order harmonics.

Innovative Design Elements. The paper introduces a 10.7-MHz fully balanced current-tunable bandpass filter with Caprio technique. This design includes unique features such as current balancing and frequency adjustment. These elements are not only novel but are presented as effective in removing unwanted harmonics and noise from the signal.

Comprehensive Evaluation Process. The proposed filter undergoes a thorough evaluation process involving synthesis, analysis, simulation, and a detailed comparison with traditional bandpass filters. The systematic approach ensures that the filter is precisely optimized to meet specific circuit requirements. The comparison with conventional filters serves to validate the effectiveness of the proposed design.

Adaptability for Integration. The paper highlights the adaptability of the proposed circuit for integration into modern communication systems. The simplicity of the circuit's structure and the suggested criteria for transistor and capacitor selection contribute to optimizing performance. This adaptability is a crucial aspect of the proposed solution.

The limitations of the study:

– although the simulation using the PSpice program is consistent, real-world applications and experimental validation are critical for confirming the actual performance of the designed circuit. Factors such as component tolerances and manufacturing variations may impact the design's real-world performance;

– selecting transistors with f_T values up to GHz can pose challenges in terms of component availability and price;

– the research primarily focuses on addressing odd-order noise in circuits attributed to gain and limited harmonic distortion. However, the generalization of the results to a broader context of communication systems may require further validation.

Directions for further research:

– conduct practical experiments and prototyping to validate the simulation results. Real-world testing will help identify any discrepancies between theoretical models and actual circuit performance, ensuring the reliability and applicability of the proposed design;

– analyze the behavior of the bandpass filter under non-ideal conditions such as variations in temperature, component tolerances, and aging effects. This will contribute to a more realistic assessment of the circuit's robustness in practical scenarios;

– explore advanced integration techniques to further develop the circuit into an integrated circuit (IC). This could involve miniaturization, reduced power consumption, and enhanced manufacturability, making it more appealing for mass production and integration into commercial communication devices.

4. Conclusions

This paper introduces a 10.7-MHz fully balanced current-tunable bandpass filter using the Caprio technique. The newly developed circuit is symmetrical, featuring differential signals and exhibiting lower total harmonic distortion (THD). Additionally, the structure of the developed circuit is not overly complex and can be further developed into an integrated circuit. The results obtained from simulations using the PSpice program and the calculations are consistent. Analyzing the transfer characteristics of transistor differential amplifier circuits with linear characteristics, it is observed that the device's sensitivity to the response at the center frequency (f_0) has a constant value between –1 and 1, which does not change with the variable value. The center frequency (f_0) is linear with an adjustable bias current (I_f) up to the third order of the circuit size. The maximum value of the center frequency (f_0) is approximately 138.995 MHz at the lowest capacitor value of 1 pF and the resistance values of R_L and R_{ee} are set to 10 Ω.

Suggestions for selecting transistors in the circuit transistors should be chosen with high f_T values (i.e., with frequencies up to GHz) as they influence the circuit's frequency, leading to a higher center frequency. Additionally, the capacitors used in the circuit should have low capacitance values because this will result in a higher center frequency and will also impact harmonic distortion, as suggested by the Caprio technique.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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