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THE DEVELOPMENT A FULLY-BALANCED CURRENT-TUNABLE FIRST-ORDER LOW-PASS FILTER WITH CAPRIO TECHNIQUE

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Abstract

This paper presents the development and design of a fully-balanced current-tunable first-order low-pass filter with Caprio technique, which could include the design and implementation of a first-order low-pass filter circuits. The filter consists of six bipolar junction transistor (BJT) and a single capacitor. The filter construction uses a bipolar junction transistor (BJT) as the main device and a single capacitor. A fully-balanced current-tunable first-order low-pass filter with Caprio technique developed. The architecture of the circuit is quite simple and proportional, symmetrical with signs of difference. Circuits developed into integrated circuits act like basic circuits for frequency filter circuits, current modes with Caprio techniques, obtained by improving the first-order low-pass filter for signal differences with incoming impedances. Adjusting the parameters of the circuit with the caprio technique achieves the optimal parameter value for correcting the total harmonic distortion value.

The results of testing the operation of the circuit, a fully-balanced current-tunable first-order low-pass filter with Caprio technique developed and designed using the PSpice program. The simulation results showed good results in line with predicted theoretical analysis. The sensitivity of the device to the center frequency (ω_0) response is low and independent of variables, the angular frequency is linear with wide current adjustment throughout the sweeping range of a wide frequency range, with a wide range of over tree orders of magnitude. Therefore, fully-balanced current-tunable first-order low-pass filter developed is very suitable to apply various applications regarding low frequency signal filtration, for example in biomedical systems, for example.

Keywords: fully balanced, low-pass filter, current-tunable, sensitivities, harmonic distortion, Caprio technique.

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1. Introduction

The rapid development of information technology and the high rate of technological change led to the development of various sciences [1]. To meet the boundless needs of these consumers, one of the fields of interest in the development of facilitating livelihoods is the electronics industry, which is known as a leap forward development since the electronics industry is the first level industry that plays a role in the development of other industries. Including the daily life of human beings when looking around let's find electronic inventions scattered everywhere, such as radios, televisions, telephones, stereos, computers, etc. If to look at the invention, let's find that it consists of various circuits such as amplifier circuits, frequency filter circuit, signal generator circuit, and the circuit that is important is the frequency filter circuit.

Filter circuits can be divided into two types: Passive filters and Active filters. The function of the filter circuit is to select the desired frequencies or cut off the unwanted frequencies. The use of a frequency filter is to filter out interference or to remove the message signal from the carrier wave in the radio system. The filter circuit can be further divided into four functional types, Low pass filter: LPF, High pass filter: HPF, Band pass filter: BPF, Notch filter or Eliminate filter: BEF and Low-pass filters are important and have a wide range of applications. For example, in mobile communication systems analog signal processing and in biomedical systems [2–8]. The low-pass filter to detect biological signals generally uses a voltage in the range of 1V–100 mV and a cut-off frequency below 100 Hz [9–13]. Design the first-order Low-pass by VFOA, [14, 15] presents a first-order low-pass filter of providing cutoff frequencies. The circuit is intended for signal conditioning applications, particularly for use with very low frequency physiological and cutoff frequency the reported filter outperforms previous filters from the literature, [16]. Presents a reconfigurable fully differential filter the proposed filter topology provides increased immunity to external noise, reduced even-order harmonics, high resolution capability and reconfigurability. It is usually desirable to have the fully balanced circuits with different signals [17–19]. [20–24] as differential input current follower.

The papers presented a technique of circuit design that has many advantages such as normal band, frequency adjustable with current. Wide dynamic range and band and low total harmonic distortion. However, the above technique needs complex circuits suffered from repeated phase-noise.

In this paper, a first-order low-pass filter circuit is presented, which applies the Caprio technique to a circuit in which the synthesized circuit can adjust the cut-off frequency with current-tunable using the principle of resistance r_e notch, *pn* connector bipolar transistor. In addition, the structure of the circuit is symmetrical, simple and uncomplicated, using few components, making the circuit suitable to be built on a chip.

2. Materials and methods

2. 1. Object and aim of the study

This research presents the development and design of a fully-balanced current-tunable first-order low-pass filter with Caprio technique.

The objectives are as follows:

– to develop and design a fully-balanced current-tunable first-order low-pass filter with Caprio technique;

– to compare the performance of the development circuit and design a fully-balanced current-tunable first-order low-pass filter with Caprio technique that was designed in theory with the simulation by PSpice.

2. 2. Circuit Description

Fig. 1, *a* shows a fully-balanced current-tunable first-order low-pass filter with Caprio technique, where the structure of the synthetic circuit is based on Six identical npn transistors are T1 to T6, one capacitor C, and one I_f current source, where a small differential signal of the input voltage (V_{in}) is fed to node *A* with node *B*, or the base pin of the T3 and T4 transistors, the small difference signal of the output voltage (V_o) is the node *D* and *E*, or the emitter pin of the transistors T3 and T4.

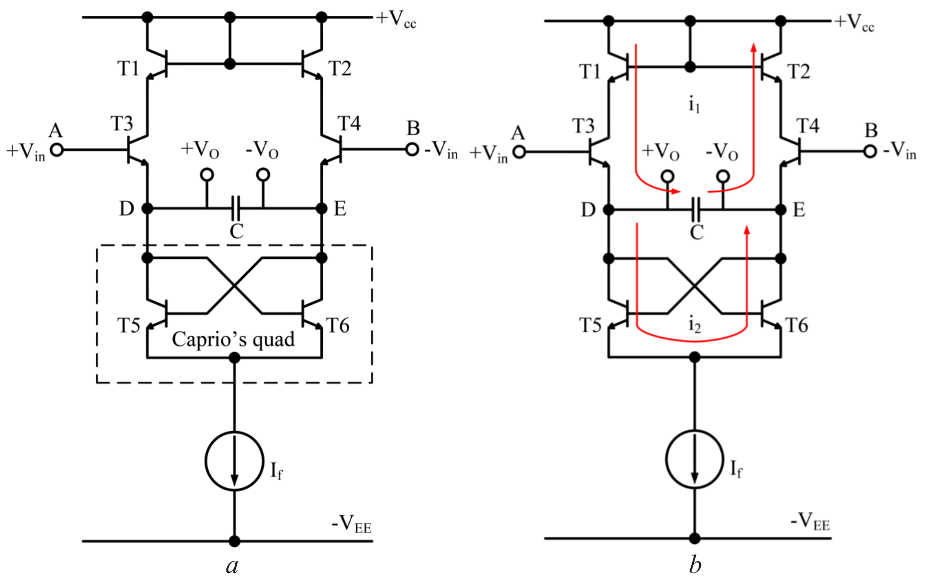

Fig. 1. A fully-balanced current tunable first-order low-pass filter with CAPRIO technique:
a – proposed circuit realization; *b* – ideal analysis

The cut-off frequency of the first-order low pass filter is typically set at the magnitude and phase shift of the V_O/V_{in} transfer function at –3 dB and –45 degrees, respectively, where the cut-off frequency off the frequency of the circuit can be adjusted using a current source, I_f bias resistance value of $R=2r_e$ obtained from transistors T1 and T2, where the value current sinks I_f may be implemented through the conventional Wilson current mirror.

2. 3. Ideal Analysis

Referring to the circuit shown in **Fig. 1, *b*** consider the signal at the input voltage amplified signal with a small difference (V_{in}), when fed to node *A* and node *B* or the base pin of the transistors T3 and T4. This results in a small difference signal of the input current i_d flowing through the loading impedance Z_1, formed by transistors T1, T2, T3 and T4, where the value of Z_1 has the value shown in (1):

$$Z_1 = 4r_e. \qquad (1)$$

It also results in a small difference in signal current, i_e flow through the loading impedance Z_2 between nodes *D* and *E*, where the value of Z_2 is shown in (2):

$$Z_2 = \frac{1}{(1+sC2r_e)}. \qquad (2)$$

Therefore, it is possible to obtain the current i_1 as shown in (3):

$$i_1 = \frac{V_{in}}{4r_e}. \qquad (3)$$

The current i_2 at the emitter terminals of transistors T3 and T4 is shown in (4):

$$i_2 = \frac{i_1}{(1+sC2r_e)}. \qquad (4)$$

So to get a differential V_O/V_{in} voltage of the first-order low-pass filter as equal to (5):

$$\frac{V_O}{V_{in}} = \frac{1}{2(1+sC2r_e)}. \qquad (5)$$

From equation (5) it is possible to find the value as shown in (6):

$$\tau = CR = \left(\frac{2C4V_T}{I_f}\right). \qquad (6)$$

Where the V_T value shown in (6) is the thermal voltage of the *pn* junction of the transistor is approximately 25 mV at room temperature:

$$\frac{V_O}{V_{in}} = \frac{1}{(2+\tau s)}. \qquad (7)$$

(7) shows the transfer function of the first-order low-pass filter in which the corner frequency of such filter circuits is shown in (8):

$$\omega_0 = \frac{1}{\tau} = \frac{I_f}{2C4V_T}. \qquad (8)$$

Equation (8) shows that the corner frequency can be adjusted by bias, the current I_f value, as it is named «current-tunable low pass filter».

2. 4. Caprio's quad of Volterra series analysis

A fully-balanced current-tunable first-order low-pass filter with Caprio technique is presented. An analysis of the 3rd-order Volterra series can be described at intermodulation component (IM3) of the output voltage V_{out}. At the frequency as shown in (9):

$$IM3_{Cap} \approx \left| \frac{A_{in}^2}{8g_m^3 R_{ee}^3 V_T^2} \frac{f}{f_T} \right|, \quad (9)$$

where these parameters A_{in}, g_m, R_{ee}, f_T are described in reference [18, 25] IIP3. From (9) it is possible to rearrange the equation as shown in (10) where $IM3_{Cap}=1$ is set:

$$VIIP3_{Cap} \approx \sqrt[2]{2V_T} \sqrt{\frac{g_m^3 R_{ee}^3 f_T}{f}}. \quad (10)$$

From equation (10), $VIIP3_{Cap}$ is the value of the reference 3rd-oder input, of the Caprio's quad extraction point voltage, the $VIIP3_{Cap}$ equation can be simplified as shown in (11):

$$VIIP3_{Cap} \approx \sqrt{\frac{f_T I_T^3 R_{ee}^3}{f V_T}}, \quad (11)$$

where the I_T seen in equation (10) is the current total consumption.

2. 5. Sensitivities

The sensitivity of the parameters within the circuit is an important aspect that the designer will attribute to the best design or construction of the circuit. The symbol used is S to indicate the sensitivity of a parameter such as sensitivity of parameters y with changes of components or independent variable x [18, 26]. Due to heat voltage V_T, capacitance C and current sync. On the off chance that the impact of temperature on the corner recurrence is additionally shown as appeared within the condition (7). Subsequently, **Table 1** shows the affectability. The affectability is generally consistent between –1 and 1. Such affectability isn't the same as the existing strategies [26, 27].

Table 1

Sensitivity S_x^y where (C, ω_0), (V_T, ω_0) or (I_f, ω_0)

$S_C^{\omega_0}$	$S_{I_f}^{\omega_0}$	$S_{V_T}^{\omega_0}$
–1	1	–1

3. Results and discussion

The circuit, a fully-balanced current-tunable first-order low-pass filter with Caprio technique shown in **Fig. 1**, was simulated using PSpice [28] using npn transistors are modeled by Q2N2222A. In the simulation, where the value The transistor f_T is 300 MHz. **Fig. 2** shows a simulation of the V_O/V_{in} frequency response at room temperature using an I_f operation of 500 µA and a capacitance C of 10 nF. The circuit response has a gain of 36.8 dB and the circuit response has a phase margin of –89.42 degrees with a gain bandwidth in units of 256.45 kHz.

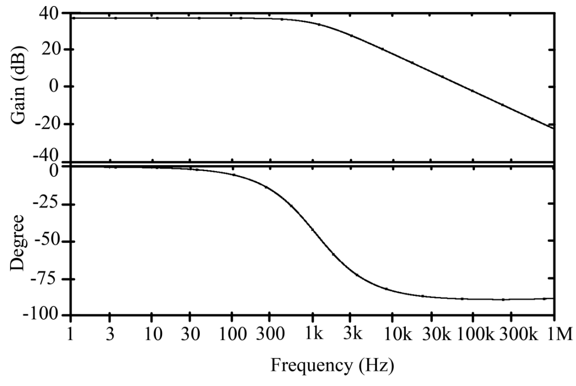

Fig. 2. The frequency response of V_O/V_{in} at room temperature with the I_f current set at 500 µA and the capacitance C taken at 10 nF

Fig. 3, shows the magnitude (dB) and phase shift (degree) of V_O/V_{in} in relation to the frequency (Hz) simulated using a capacitor with a value of C = 10 nF and modify the values as follows I_f = 100 µA, 300 µA and 1 mA from the comparison shown in **Fig. 3,** It can be seen that the frequency is compared with the magnitude of V_O/V_{in} becomes – 3 dB for each value respectively 260.62 Hz, 693.59 Hz and 2.095 kHz, and the corresponding (degree) V_O/V_{in} phase shift for each of the I_f values is approximately – 45 degrees.

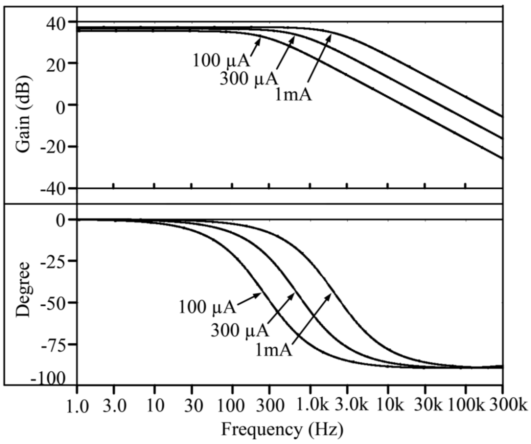

Fig. 3. Shows the magnitude (dB) and phase shift (degree) of V_O/V_{in} compared to the frequency (Hz) using capacitance C = 10 nF and adjusted for current I_f = 100 µA, 300 µA, 1 mA

Fig. 4, The simulation results of both the corner frequency (Hz) and the phase shift with the corresponding value of change (degrees) of V_O/V_{in}, where the magnitude value of V_O/V_{in} becomes – 3 dB, I_f (A) bias current, using capacitor C = 10 nF selected, for comparison purposes the ideal (expected) result is included. **Fig. 4** shows that both the expected result and the simulated result are consistent, and that the f_0 frequency is linearly for the current-tunable in the sweep range «Wide frequency» with around 3rd – order.

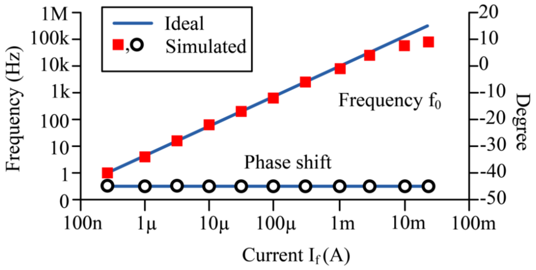

Fig. 4. Plot of the corner frequency (Hz) comparing the phase shift (degree) of V_O/V_{in} with versus the bias I_f (A) using a constant capacitance C = 10 nF

Fig. 5 shows the simulation result of the corner frequency (Hz) and the V_O/V_{in} phase shift comparison (degree) shows that the magnitude of the V_O/V_{in} becomes – 3 dB compared to the modulation. Change the capacitance C with constant bias current I_f 500 µA for comparison. An ideal (expected) result is included. From **Fig. 5**, it can be seen that both the expected result and the simulation result are linear. A minimum frequency setting capacitance of 10 pF is used, f_0 frequencies can be expected at 670 kHz.

Fig. 6 shows the simulation results of the harmonic spectra between Conventional Circuit and Circuit with Caprio's quad T1 to T6, where Caprio's quad transistors T5 and T6 are short-circuited. The results showed that Conventional Circuit has high frequencies of 4.25 kHz, 4.40 kHz, and 4.65 kHz when compared to Circuit with Caprio's quad, resulting in reduced order of those high harmonics, where total harmonic distortion (THD) is reduced from 239.22 % to 68.43 %.

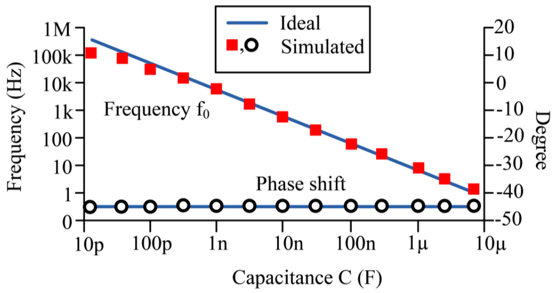

Fig. 5. Plot of the corner frequency (Hz) comparing the phase shift (degree) of V_O/V_{in} with versus the capacitance (C), using bias current I_f 500 µA

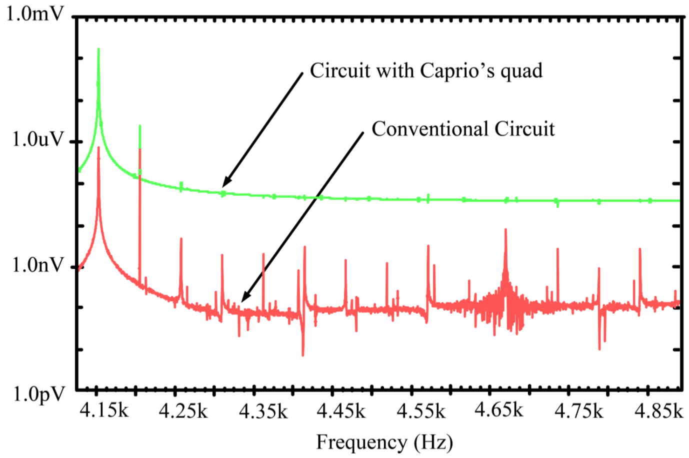

Fig. 6. Comparison of harmonic spectra of conventional circuit compared to Circuit with Caprio's quad

It can be seen from the simulation of the proposed fully-balanced current-tunable first-order low-pass filter with Caprio technique demonstrates circuit efficiency with high linearity angular wide-frequencies, bias current-tunable, and the magnitude of the harmonic distortion is reduced. The results from the simulation of the circuit and the calculated values are consistent. Selection of transistors for use in the circuit should choose better transistors and higher frequencies f_T (e.g. with frequencies up to GHz) because it affects the frequency of the circuit by getting a higher frequency of the circuit and choosing the capacitors used. With the circuit should choose a lower capacitance value of the capacitor will result in a higher frequency of the circuit. However, the proposed fully-balanced current-tunable first-order low-pass filter with Caprio technique is limited as the Q2N2222A transistor has an f_T value of 300 MHz.

The next development approach should be to develop a circuit to be able to adjust the frequency band to be wider than before or to be able to adjust the frequency band throughout the current adjustment band. In addition, the circuit may be developed for the signal frequency to be higher than before because the operating frequency (f_0) depends on the I_f current and the capacitance of the capacitor connected in the circuit. Therefore, if a transistor can be built to have a large collector current (i_c) and reducing the capacitance value will result in a higher frequency (f_0).

4. Conclusions

A fully-balanced current-tunable first-order low-pass filter with Caprio technique has an internal structure of the circuit that is symmetrical with different signals. The circuit presented is relatively simple and uncomplicated, suitable to be integrated on-chip. The test results of the simulated and ideal circuits are consistent. A simple procedure has been proposed for estimating the transfer characteristics of linearized pair emitter pairs. The sensitivity of is constant between –1 and 1 independent of variables. The Corner frequency is capable of high linearity gain over a wide frequency sweep at the 3rd-order of magnitude. The maximum active angle frequency is approximately 198.8 kHz. By using better transistors of much higher f_T (e.g. in multiple GHz regions) and much lower C values (e.g. using stray capacitance), the corner frequencies are much higher. This results in reduced harmonic distortion as suggested by the Caprio technique. Therefore, fully-balanced current-tunable first-order low-pass filter developed is very suitable to apply various applications regarding low frequency signal filtration, for example in biomedical systems, for example.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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References

[1] Mammadova, M. (2019). Methods for fuzzy demand assessment for it specialties. EUREKA: Physics and Engineering, 4, 23–33. doi: http://doi.org/10.21303/2461-4262.2019.00939

[2] Csipkes, G., Hintea, S., Csipkes, D., Rus, C., Festila, L., Fernandez-Canque, H. (2009). A highly linear low pass filter for low voltage reconfigurable wireless applications. Journal of Automation, Mobile Robotics and Intelligent Systems, 3 (2), 76–81.

[3] Pérez-Bailón, J., Márquez, A., Calvo, B., Medrano, N. (2018). A 0.18 μm CMOS Widely Tunable Low Pass Filter with sub-Hz Cutoff Frequencies. 2018 IEEE International Symposium on Circuits and Systems (ISCAS). doi: http://doi.org/10.1109/iscas.2018.8351166

[4] Tran, M., Kuwana, A., Kobayashi, H. (2020). Design of Active Inductor and Stability Test for Ladder RLC Low Pass Filter Based on Widened Superposition and Voltage Injection. Proceedings of The 8th IIAE International Conference on Industrial Application Engineering 2020. doi: http://doi.org/10.12792/iciae2020.038

[5] Karki, J. (2000). Active low-pass filter design. Texas Instruments application report. Available at: https://www.ti.com/lit/an/sloa049b/sloa049b.pdf?ts=1615152409596

[6] Arbet, D., Nagy, G., Kovác, M., Stopjaková, V. (2015, April). Fully differential difference amplifier for low-noise applications. 2015 IEEE 18th International Symposium on Design and Diagnostics of Electronic Circuits & Systems, 57–62. doi: http://doi.org/10.1109/ddecs.2015.38

[7] Langhammer, L., Dvorak, J., Sotner, R., Jerabek, J. (2017). Electronically tunable fully-differential fractional-order low-pass filter. Elektronika ir Elektrotechnika, 23 (3), 47–54. doi: http://doi.org/10.5755/j01.eie.23.3.18332

[8] Prathepha, K., Sa-ngiamvibool, W. (2021). The investigation of natural-rubber for improving self-powered heat detector based on thermoelectric generators. EUREKA: Physics and Engineering, 6, 65–73. doi: http://doi.org/10.21303/2461-4262.2021.002117

[9] Solís-Bustos, S., Silva-Martínez, J., Maloberti, F., Sánchez-Sinencio, E. (2000). A 60-dB dynamic-range CMOS sixth-order 2.4-Hz low-pass filter for medical applications. IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing, 47 (12), 1391–1398. doi: http://doi.org/10.1109/82.899631

[10] Krishna, J. R. M., Laxminidhi, T. (2019). Widely tunable low-pass g_m– C filter for biomedical applications. IET Circuits, Devices & Systems, 13 (2), 239–244. doi: http://doi.org/10.1049/iet-cds.2018.5002

[11] Bonargent, T., Menard, T., Pigeon, E., Gehan, O. (2019). Observer and first-order low-pass filter based attitude estimation for rigid bodies subject to external acceleration. 2019 IEEE 58th Conference on Decision and Control (CDC). doi: http://doi.org/10.1109/cdc40024.2019.9030202

[12] Hasan, M. N., Lee, K. S. (2014). A wide linear output range biopotential amplifier for physiological measurement frontend. IEEE Transactions on Instrumentation and Measurement, 64 (1), 120–131. doi: http://doi.org/10.1109/tim.2014.2332240

[13] Kalyani, V., Parashar, N. (2015). First Order Low Pass Butterworth Filter Realization using VFOA and their Applications. Journal of Management Engineering and Information Technology, *2* (3), 28–31.

[14] Rodriguez-Villegas, E., Casson, A. J., Corbishley, P. (2011). A subhertz nanopower low-pass filter. IEEE Transactions on Circuits and Systems II: Express Briefs, 58 (6), 351–355. doi: http://doi.org/10.1109/tcsii.2011.2158165

[15] Ravelo, B. (2016). First-order low-pass negative group delay passive topology. Electronics Letters, 52 (2), 124–126. doi: http://doi.org/10.1049/el.2015.2856

[16] Khan, I. A., Masud, M. I., Moiz, S. A. (2015). Reconfigurable fully differential first order all pass filter using digitally controlled CMOS DVCC. 2015 IEEE 8th GCC Conference & Exhibition. doi: http://doi.org/10.1109/ieeegcc.2015.7060082

[17] Uhrmann, H., Zimmermann, H. (2009). A fully differential operational amplifier for a low-pass filter in a DVB-H receiver. 2009 MIXDES-16th International Conference Mixed Design of Integrated Circuits & Systems. doi: http://doi.org/10.1109/ddecs.2009.5012124

[18] Wongmeekaew, T., Sa-ngiamvibool, W. (2016). A Fully-Balanced Current-Tunable Integrator with CAPRIO. Parameters, 2 (33), 8.

[19] Duque-Carrillo, J. F., Torelli, G., Perez-Aloe, R., Valverde, J. M., Maloberti, F. (1995). Fully differential basic building blocks based on fully differential difference amplifiers with unity-gain difference feedback. IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, 42 (3), 190–192. doi: http://doi.org/10.1109/81.376865

[20] Shah, P. (1993). A fully integrated continuous-time 1Hz low-pass filter with high dynamic range and low distortion. ESSCIRC'93: Nineteenth European Solid-State Circuits Conference, 1, 182–185.

[21] Tang, N., Nguyen, B., Molavi, R., Mirabbasi, S., Tang, Y., Zhang, P., et. al. (2016). Fully integrated buck converter with fourth-order low-pass filter. IEEE transactions on power electronics, 32 (5), 3700–3707. doi: http://doi.org/10.1109/tpel.2016.2593049

[22] Zhang, Y., Li, N., Xiang, Y., Wang, D., Zhang, P., Wang, Y. et. al. (2020). A flexible non-enzymatic glucose sensor based on copper nanoparticles anchored on laser-induced graphene. Carbon, 156, 506–513. doi: http://doi.org/10.1016/j.carbon.2019.10.006

[23] Lertkonsarn, S. (2021). A Fully-Balanced Current-Tunable Gm-C Low Pass Filter. Mahasarakham International Journal of Engineering Technology, 7 (1), 85–88.

[24] Murphy, D., Rael, J. J., Abidi, A. A. (2009). Phase noise in LC oscillators: A phasor-based analysis of a general result and of loaded $ Q $. IEEE Transactions on Circuits and Systems I: Regular Papers, 57 (6), 1187–1203. doi: http://doi.org/10.1109/tcsi.2009.2030110

[25] Pan, H. Y. M., Larson, L. E. (2007). Highly linear bipolar transconductor for broadband high-frequency applications with improved input voltage swing. 2007 IEEE International Symposium on Circuits and Systems. doi: http://doi.org/10.1109/iscas.2007.377908

[26] Sa-Ngiamvibool, W. (2013). A 10.7-MHz Fully Balanced, Q-of-267, 103-dB-Dynamic-Range Current-Tunable Gm-C Band-pass Filter. Przeglad Elektrotechnicany, 89 (10), 204–209.

[27] Comer, D. T., Comer, D. J., Gonzalez, J. R. (1997). A high-frequency integrable bandpass filter configuration. IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing, 44 (10), 856–861. doi: http://doi.org/10.1109/82.633445

[28] Affirma, A., Cierto, E., Mercury Plus, Q., Radium, S. E. (1985). User's Guide. Cadence Design Systems, Inc. All rights reserved. Available at: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.706.4121&rep=rep1&type=pdf

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