IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.414 ⪤ Peer-reviewed & Refereed journal ⪤ Vol. 13, Issue 8, August 2025

DOI: 10.17148/IJIREEICE.2025.13815

CARBON NANOTUBE FIELD EFFECT TRANSISTOR (CNTFET)-BASED-OPERATIONAL TRANSCONDUCTANCE-AMPLIFIER (OTA) IMPLEMENTATION IN ACTIVE LOW-PASS-FILTER (LPF) AT 14 NM TECHNOLOGY NODE: DESIGNING, SIMULATION, AND PERFORMANCE EVALUATION SUITABLE FOR BIOMEDICAL SIGNAL FILTRATION

Samia Bashiruddin[1*], Pallavi Gupta[1*], M. Nizamuddin[2]

Ph.D. Research Scholar, EECE, Sharda University, Greater Noida, India[1]

Professor, EECE, Sharda University, Greater Noida, India[1]

Professor, ECE Jamia Millia Islamia, Greater Noida, India[2]

Abstract: The frequency overlap between biomedical signals and noise highlights the critical need for effective signal processing and filtering to ensure precision in radio diagnostics. This work introduces the design of a 14 nm CNFET-OTA-based low-pass filter (LPF) suitable for physiological signal filtration. A second-order LPF architecture integrating CNFET-OTA was proposed and simulated using HSPICE. The filter achieved a cut-off frequency of 100.7 Hz, an average power dissipation of 141.8 nW, a quality factor of 0.707, and a phase margin of 134°, confirming its applicability in biomedical domains. Low power consumption, low cut-off frequency, with an appropriate quality factor, makes the proposed LPF well-suited for real-time bio signal processing. Aiming for low power consumption while achieving low cut-off frequency from a 0.5V power supply, CNFET-OTA-based LPFs ensure resilience in real-world applications, paving the way for future advancements in this field.

Keywords: CNTFET, OTA, HSPICE, Stanford Model, Filter, Bio Signal

I. INTRODUCTION

Filters are essential in ensuring the integrity of the desired signal by effectively removing noise and interference. In real-world scenarios, including biomedical applications, signals are often subject to various forms of unwanted noise, interference, and artifacts. As a result, the process of filtering becomes particularly challenging, requiring sophisticated techniques to maintain signal quality while minimizing unwanted distortions. This challenge is intensified by the spectral overlap between biomedical signals and noise [1]. OTAs are key components in analog and mixed-signal circuits, including variable-gain amplifiers (VGAs) and filter architectures [2-4]. An OTA-C filter with a certain gain is suitable for processing low-frequency biomedical signals [5]. The most widely used biomedical signals include Electroencephalogram (EEG), Electrocardiogram (ECG), and Electromyography (EMG). These signals each have distinct amplitude and frequency ranges, with EEG typically operating around 100 Hz, ECG at 250 Hz, and EMG at 500 Hz. [6]. Among various filter types, OTA-C filters offer a wide cut-off frequency range, making them highly suitable for signal enhancement in applications such as electrocardiograms (ECG), electromyograms (EMG), and electroencephalograms (EEG), where noise suppression is essential for signal clarity and diagnostic precision [7, 8].

DOI: 10.17148/IJIREEICE.2025.13815

Their frequency response can be finely tuned via transconductance control and capacitor scaling, supporting efficient on-chip integration [9]. CNTFET-based OTAs provide significant advantages, including higher transconductance, reduced short-channel effects, and lower power consumption—attributes enabled by superior electron mobility and minimal intrinsic capacitance, all of which contribute to enhanced performance [10]. Fig. 1 illustrates the bio signal processing system, while Table I provides an overview of the typical power consumption for various miniaturized electronic devices. This study presents design and HSPICE-based performance analysis of a CNTFET-OTA-driven low-pass filter (LPF) at the 14 nm technology node.

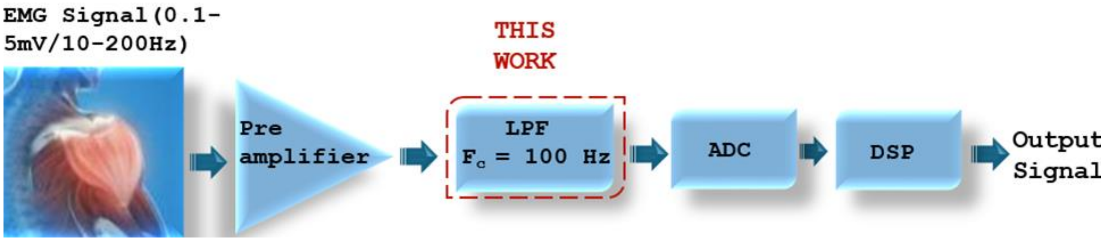

Fig.1 Block diagram for a typical biomedical acquisition system.

Table 1. Power requirements of various miniaturised devices [11].

Device description	Power Requirement
Cardiac-pacemaker	1 μW
Cardiac-Activity Sensing	0.3 μW
Electrocardiogram-amplifier	2.76 μW
Drug-pump for ophthalmic use	400 μW
Neural-Activity-Monitoring	1-10 mW
Sensor-on-Wristband	0.83 mW
Chest-Patch	0.96 mW
Spirometer	0.01 mW
Wireless-sensor-network (WSN)	71 nW

I.A. Review of CNTs and incorporation of OTA-C as an implementation into LPF

Carbon nanotubes (CNTs), formed by rolling graphene sheets into cylindrical structures, have become a focal point of extensive research because of their exceptional physical properties [12]. Carbon nanotubes primarily occur in two forms: single-walled nanotubes (SWCNTs) and multi-walled nanotubes (MWCNTs) [13, 14]. Single-walled carbon nanotubes (SWCNTs) are especially notable for their remarkable properties, including ballistic electron transport, superior thermal conductivity, outstanding mechanical strength, and a high aspect ratio. In the realm of electronics, semiconductors remain fundamental, and the distinct advantages of CNTs have shifted research attention towards CNT-based semiconductor technologies [15]. A CNTFET, utilising SWCNT or MWCNT as the channel material, serves as an alternative to conventional bulk-silicon MOSFETs [16]. Beyond pure CNT-based devices, hybrid CMOS-CNFET designs have also been proposed, demonstrating superior performance over standard CMOS, especially at nanoscale technology nodes [17, 18]. The Operational Trans conductance Amplifier (OTA), a voltage-controlled current source, can linearly process a wide range of input signals to generate corresponding output currents [19]. OTA-C filters are ideal for on-chip integration because their frequency characteristics can be easily adjusted. This is done by altering the transconductance (Gm) or changing the filter capacitance value, offering flexibility in design [1]. Low-pass filters (LPFs) play a vital role in biomedical signal processing by preserving critical components of signals (for example, the P-wave, QRS complex, and T-wave in an ECG) while attenuating high-frequency noise, thus improving diagnostic accuracy. Therefore, low-power LPF design is essential in biomedical signal acquisition systems [20]. Recent studies have shown that CNTFET-based OTA-C LPFs, even at reduced technology nodes, can function effectively with a low supply voltage while minimizing power consumption [1, 21]. Thus, the present work focuses on designing a CNTFET-OTA-C-based LPF at the 14 nm technology node for processing physiological signals effectively.

IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.414 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 13, Issue 8, August 2025

DOI: 10.17148/IJIREEICE.2025.13815

II. METHODS AND METHODOLOGY

Fig.2 represents a second-order OTA-C filter as an application of CNTFET-OTA utilising CNTs as the channel material, which combines PCNTFET and NCNTFETs. This filter topology includes OTAs (n = 02) and capacitors C1 and C2. The low cut-off frequency is obtained by selecting capacitor values C1 = 2600 pF and C2 = 1300 pF.

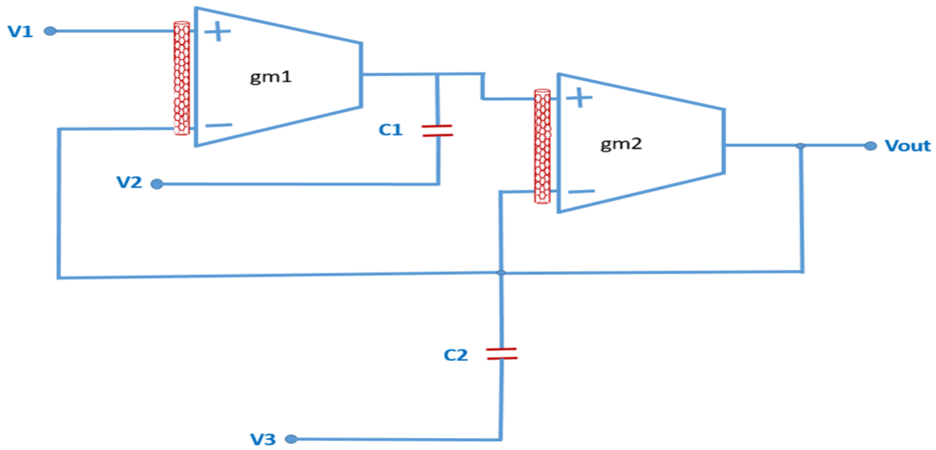

Fig. 2 Illustration of CNTFET-Gm-C low-pass filter

The input signal can be applied to V1, V2, or V3 terminals, with V_{out} serving as the output terminal. As a result, the filter can demonstrate either low-pass (LP) frequency response (FR), high-pass FR, or band-pass FR, depending on the input signal applied concerning V1, V2, and V3. A low-pass filter is realised by applying a dynamic input signal (V_{in} = 0.2mV) to V1 with grounded V2 and V3. For both the OTAs of the proposed filter structure, transconductances gm_1 and gm_2 are maintained equal. Table II presents input conditions for the proposed circuit with ω_0 and quality factor (Q). This provides the electronic tunability by adjusting g_m, which can be controlled through the bias voltage and capacitance values. The output voltage (V_{out}) for the proposed CNTFET-OTA-incorporated-LPF can be expressed as equation 1.

$$Vout = S^2C1C2V3+SC1gm2V2+gm1gm2V1 \,/\, S^2\, C1\, C2+SC1gm2+gm1gm2 \; \ldots\ldots\ldots \quad (1)$$

Table II. Various input conditions for the designed CNTFET-based Circuit.

Circuit	Input Condition	ω_0	Q
Low Pass Filter	V_{in}=V_1, V_2 = V_3 = 0	gm/√C1 C2	√C2/C1

The HSPICE simulation using the Stanford University CNTFET model [22] was executed to assess the filter's performance at the 14nm technology node with a supply voltage of 0.5V, bias voltage (V_{bias} = 0.3V), several tubes (N = 20), and a Pitch-value (S = 20). Table III outlines some of the key CNTFET parameters used in the circuit design.

Table III. Important Simulation parameters for designing CNTFET-based circuits.

Parameters	Denotation	Value
Channel-length (Physical)	Lch	14 nm
Doped-CNT-source/drain-extension-length	Lss: Ldd	14 nm
Gate-dielectric or high-K dielectric-constant-HfO_2	K_{gate}	16
Oxide-thickness	T_{ox}	4 nm
CNT diameter	D_{CNT}	1.5 nm
Interspacing of two adjacent CNTs (Pitch) (centre-to-centre)	S	20 nm
The mean-free-path-in doped-CNT-p+/n+	Leff	15 nm
The mean-free-path (in the intrinsic CNT channel)	Lgef	20 nm
CNT-work-function	ϕs	4.5
Doped CNT (Fermi Level)	Ef_o	0.6
Tubes' Chiral Vectors	(m, n)	19, 0
N in CNTFET	N	20

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering
Impact Factor 8.414 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 13, Issue 8, August 2025
DOI: 10.17148/IJIREEICE.2025.13815

III. RESULTS AND DISCUSSION

A CNTFET-OTA for the implementation of a low-pass filter is designed, and its key performance parameters are evaluated by varying tube metrics, for example, (N) and (S), given in Tables IV and V, respectively. However, the subsequent simulation was optimised at N = 20, S = 20 for an OTA to be used in LPF, keeping the rest design parameters the same.
4

III.A. Performance Evaluation by Varying Number of CNTs (N)

Improving conductivity requires identifying the optimal number of CNTs that should form the channel to carry the load current. It has been observed that increasing the number of tubes boosts the DC gain and slightly broadens the bandwidth of the CNTFET-based OTA circuit. However, output resistance (Ro) decreases as the tube count rises (Table IV), exhibiting a declining trend with an increasing number of tubes [23]. Although a higher number of tubes improves conductivity and boosts the device's drive current, it also results in greater power dissipation. For subsequent analysis of the CNTFET-OTA-based low-pass filter, the number of CNTs was optimised at 20.

Table IV. Performance evaluation of CNT-OTA by varying the number of CNTs (N) at channel length (L_{ch} = 14nm), VDD = 0.5 V, V_{bias} = 0.3, dynamic input signal Vin =0.2 mV and S=20

Tubes (N)	Gain (dB)	Average Power (nW)	Bandwidth (MHz)	Output Resistance (MΩ)	Phase Margin°
5	9.1	17.7	0.163	3.3	110
10	14.9	35.4	0.168	1.6	100
15	18.2	53.2	0.172	1.1	97
20	20.5	70.9	0.1775	0.845	95.4
25	22.19	88.6	0.182	0.676	94.4
30	23.5	106	0.186	0.563	93.7
35	24.6	124	0.191	0.483	93.3
40	25.6	141	0.196	0.422	92.9

III.B. Performance Assessment by Adjusting CNT Pitch (S)

Variations in pitch affect the output resistance and DC gain due to the screening effect. As shown in Table V, the DC gain initially increases with increasing pitch, then eventually becomes almost constant. Analytical results, presented in Table V, indicate that the bandwidth increases slightly with larger pitch values. This is attributed to reduced gate-to-channel capacitance (Cgs) for each CNT, as increased spacing allows less charge coupling per CNT. However, a high CNT packing density degrades the performance [23]. For further simulation, a pitch of 20 nm is optimised for an OTA to be used in the LPF for achieving the desired low cut-off frequency.

Table V. Performance evaluation of CNT-OTA by Varying Pitch (S) at channel length (L_{ch} = 14nm), VDD = 0.5 V, dynamic input signal Vin =0.2 mV and N = 20

Pitch (S)	Gain (dB)	Average Power (nW)	Bandwidth (MHz)	Output Resistance (MΩ)	Phase Margin°
5	15	42	0.170	1.5	99
10	19.28	62.19	0.1752	0.983	96.21
15	20.153	68.39	0.1768	0.881	95.64
20	20.5	70.91	0.1775	0.845	95.42
25	20.64	72.15	0.1778	0.828	95.32
30	20.72	72.85	0.1780	0.819	95.26
35	20.78	73.27	0.1781	0.813	95.23
40	20.81	73.55	0.1782	0.810	95.20

The simulation results show that the proposed OTA design, due to its low power consumption (70.9 nW), is well-suited for many biomedical signal processing applications (EMG, EEG, ECG). Fig.3 shows the frequency response of the CNTFET-OTA-C filter considering a supply voltage of 0.5 V and the noisy signal is applied to the LPF's input. Frequency response shows the response close to ideal with unity gain. Whereas, low power consumption of ~141nW is shown in

Fig.4. By selecting capacitance values of C1 = 2600 pF and C2 = 1300 pF, a low-pass filter with a target cut-off frequency of around 100 Hz was achieved. The design used 20 tubes (N = 20), with a dynamic input signal of 0.2 mV and a bias voltage of 0.3 V to attain the desired cut-off frequency (fc) of approximately 100 Hz. The OTA-C filter's cut-off frequency can be fine-tuned by adjusting the transconductance and optimizing the capacitors, making it well-suited for on-chip integration [9].

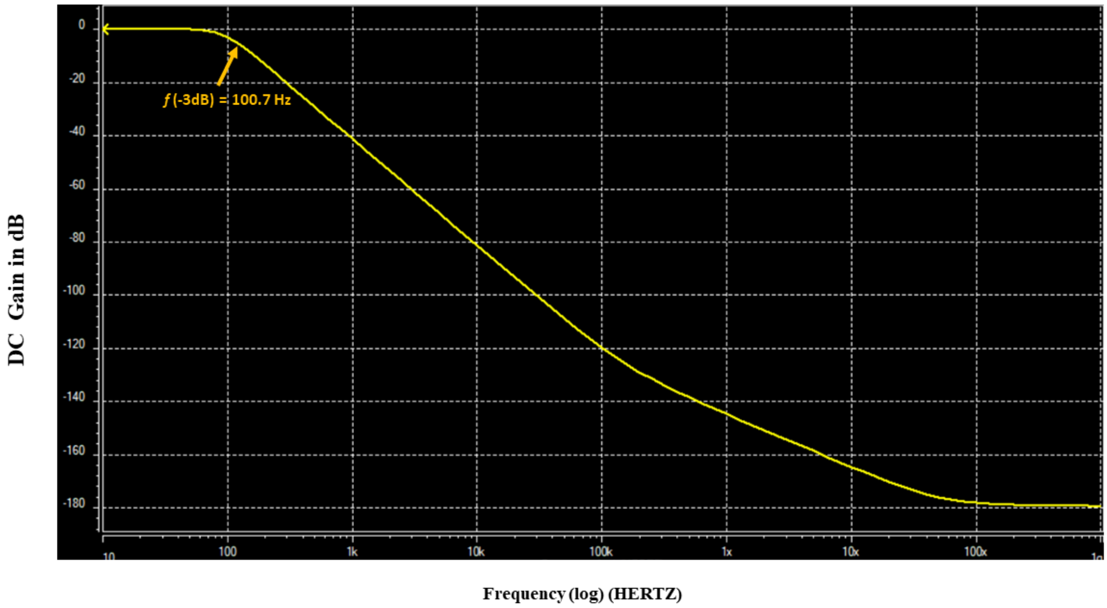

Fig. 3. Frequency Response of CNTFET-Gm-C low-pass filter

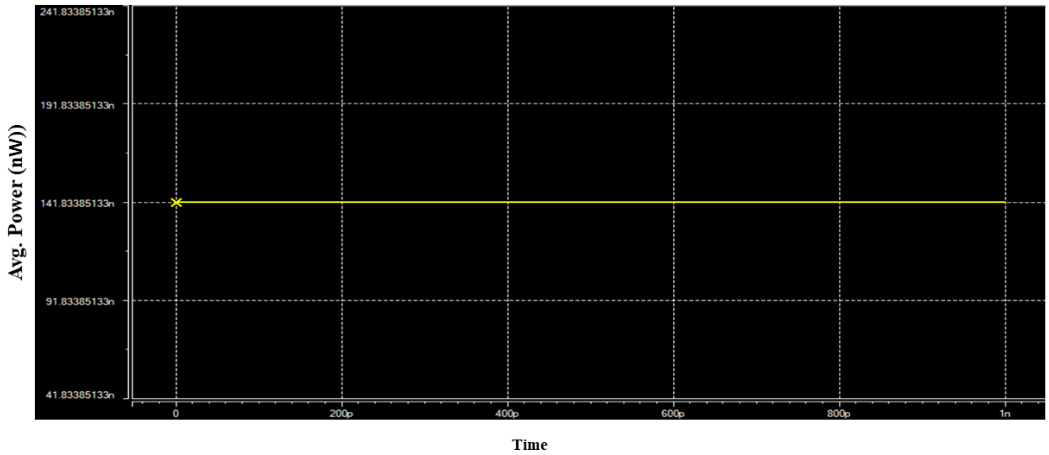

Fig. 4. Avg. Power of CNTFET-Gm-C low-pass filter

Additionally, Table VI presents several key performance metrics of the proposed LPF. The operational (supply) voltage for the proposed LPF is set at ± 0.5 V, with a dynamic input of 0.2 mV, which is lower than the input values used in many previous LPF designs found in earlier research studies [21, 23, 24]. The power consumption of the proposed LPF is also lower compared to many other filters reported in the literature, as summarized in Table VI. Additionally, the proposed low-pass filter (LPF) demonstrates improved efficiency, with a power consumption of ~ 141 nW at ultra-scaled technology node, outperforming several previously reported LPFs [3, 21, 23, 25]. An LPF that operates with low power consumption and at a low supply voltage demonstrates its suitability for bio signal processing applications [26]. Furthermore, the achievement of a cut-off frequency (f_c) of approximately 100Hz (Fig. 3) underscores its high suitability as the f_c range of a few Hz to nearly 150 Hz is required for most biomedical applications [1, 27]. For example, the EMG signal carries usable energy across the frequency range of 0-500 Hz, with the majority of its energy concentrated between 50-150 Hz [28]. EMG noise, which occurs at frequencies above 100 Hz, can be effectively removed using a low-pass filter with an appropriately selected cut-off frequency [29].

DOI: 10.17148/IJIREEICE.2025.13815

Also, the phase margin of 134° shows good stability. Therefore, it is important to note that a minimum phase margin of 45° is required for stability, with 60° generally considered more desirable [24]. Based on its phase margin, the proposed Filter demonstrates a high level of stability. Moreover, the proposed Filter achieved a quality factor of 0.707, suggesting that the low-pass filter (LPF) exhibits a smooth roll-off characteristic without introducing oscillations [30]. Finally, our results ($f_c = 100$ Hz) are considered good in terms of low power consumption using a low supply **(**± 0.5V) and dynamic input **(**0.2 mV), advanced technology node (14 nm node) and at much lower values of capacitances C1 and C2 as compared with the result of 100Hz cut-off frequency in the research of Rahane et.al., 2018 [1]. The dynamic input signal of 0.2 mV optimised for the proposed LPF is suitable for filtering various low amplitude biomedical signals as the biological signal amplitude varies from 15 µV to 5 mV (ECG: 100 µV to 5 mV/0.05 to 250 Hz); (EEG: 15 to 100 µV/ 0.05 to 60 Hz); (EMG: 0.1 to 5 mV/ 10 to 200 Hz) [5, 27, 31].

Also, S. Sinha et al. mentioned that Fin FET will be the choice for extending CMOS scaling beyond the 20 nm node, do not include bulk CMOS predictive technology models (PTM) in sub-20 nm, and discussed sub-20 nm Fin FET PTMs as an alternative, implying sub-20 nm CMOS PTM models are not found in PTM archives [32]. Scaling gate lengths below 32 nm poses challenges in terms of performance and leakage. The shift to 3D Fin FET structures resolved this, offering higher density and better low-voltage performance than planar transistors. As a result, all advanced logic nodes now use Fin FETs [33]. Moreover, according to the University of Minnesota's site (mec.umn.edu/PTM), under the previous research projects, it mentioned, "These predictive model files are compatible with standard circuit simulators and scalable with a wide range of process variations. PTM created model files for bulk CMOS until the 22nm node, Fin FET device down to the 7nm node, and carbon nanotube (CNT) device" indicating the unavailability of sub-20nm bulk CMOS PTM models. University of Minnesota Research page (PTM), accessed on 6th August 2025 [34]. Thus, it supports the design and implementation of OTA at the 14nm node (sub-20nm) using CNT-based FET (CNTFET) with improved low-voltage performance compared to planar bulk CMOS. To the best of our knowledge, information on CNTFET-Gm-C LPF at the 14nm technology node is lacking, which signifies the novelty of this work. A comparison of various performance parameters for the power-efficient proposed LPF and earlier conceptualised designs is presented in Table VI.

Table VI. A comparison of the performance parameters of the proposed LPF with those of other reported LPF designs.

Ref	Technology	Supply Voltage	Power consumption	Quality Factor (Q)	Cut-off Freq. (f_c)	Phase Margin	No. of Active Devices used	No. of Cap/ Resistor (C/R)
[1]	32nm-Hybrid	-	433nW	-	100Hz	-	2 OTAs	2C/0R
[23]	32nm-CNTFET	± 0.9 V	-	1	35.5 MHz	-	2 OTAs	2C/1R
[24]	32nm-CNTFET	± 0.9 V	-	-	69.98 MHz	-	2 OTAs	2C/0R
[25]	32nm-CNTFET	± 0.2 V	447 nW	0.97	-	-	8/11 inverters	2C/0R
[35]	22nm-CMOS	± 0.7 V	0.44mW	-	-	-	2 Current Conveyors	2C/0R
[35]	22nm-CNTFET	± 0.7 V	0.98µW	-	-	-	2 Current Conveyors	2C/0R
[21]	22nm-CNTFET	± 0.9 V	0.3840µW	-	-	-	2 OTAs	2C/0R
This Work	14 nm-CNTFET	± 0.5V	141.8nW	0.707	100.7 Hz	134°	2 OTAs	2C/0R

IV. FUTURE DIRECTION

Future research will explore the development of various diagnostic and therapeutic biomedical devices utilising the proposed CNT-OTA based filter block, along with experimental validation of the simulation results will be the future direction for this research.

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering
Impact Factor 8.414 ⪤ Peer-reviewed & Refereed journal ⪤ Vol. 13, Issue 8, August 2025
DOI: 10.17148/IJIREEICE.2025.13815

V. CONCLUSION

The OTA-C filter, designed at a 14nm technology node, is intended for biomedical signal processing, with CNTFET-OTA technology serving as the core component in the analog circuits discussed in this paper. CNTFETs are proposed as a promising alternative to traditional silicon MOSFETs for use in ultra-scaled devices. The proposed filter operates at a low supply voltage (0.5V), resulting in a low cut-off frequency (fc =100 Hz) with a low power consumption of ~141nW and thus possesses relatively excellent performance.

REFERENCES

[1] S. Rahane, A. Kureshi, and G. Kharate, "OTA-C filters for biomedical signal processing applications using hybrid CMOS-CNFET technology," in *2018 International Conference on Intelligent and Innovative Computing Applications (ICONIC)*, 2018: IEEE, pp. 1-5.
[2] M. Mobarak, M. Onabajo, J. Silva-Martinez, and E. Sanchez-Sinencio, "Attenuation-predistortion linearization of CMOS OTAs with digital correction of process variations in OTA-C filter applications," *IEEE Journal of Solid-State Circuits,* vol. 45, no. 2, pp. 351-367, 2010.
[3] J. Chen, E. Sanchez-Sinencio, and J. Silva-Martinez, "Frequency-dependent harmonic-distortion analysis of a linearized cross-coupled CMOS OTA and its application to OTA-C filters," *IEEE Transactions on Circuits and Systems I: Regular Papers,* vol. 53, no. 3, pp. 499-510, 2006.
[4] R. Marston, "Understanding and using OTA OP-AMP ICs," *Nults & Volts Magazine,* pp. 70-74, 2003.
[5] Y. Yin *et al.*, "An Ultra-Low-Voltage Transconductance Stable and Enhanced OTA for ECG Signal Processing," *Micromachines,* vol. 15, no. 9, p. 1108, 2024.
[6] M. B. Elamien and S. A. Mahmoud, "Analysis and design of a highly linear CMOS OTA for portable biomedical applications in 90 nm CMOS," *Microelectronics journal,* vol. 70, pp. 72-80, 2017.
[7] A. Choudhary, M. Zadoo, and S. A. Imam, "Simulation and Analysis of OTA-C Ladder Butterworth filter for Sensors & Biomedical Applications."
[8] A. Dixit, A. Kumar, S. Shukla, and G. Srivastava, "Electronically Tuneable Low Power Cascaded OTAC Fifth Order Notch Filter for Front End ECG Processing System," in *2024 5th International Conference on Smart Electronics and Communication (ICOSEC)*, 2024: IEEE, pp. 397-403.
[9] R. K. Ranjan, S. P. Yalla, S. Sorya, and S. K. Paul, "Active comb filter using operational transconductance amplifier," *Active and Passive Electronic Components,* vol. 2014, no. 1, p. 587932, 2014.
[10] T. Khurshid, S. Fatima, F. A. Khanday, F. Bashir, F. Zahoor, and F. A. Hussin, "Carbon nanotube field effect transistor (CNTFET) operational transconductance amplifier (OTA) based design of high frequency memristor emulator," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields,* vol. 34, no. 2, p. e2827, 2021.
[11] M. N. Hasan, S. Sahlan, K. Osman, and M. S. Mohamed Ali, "Energy harvesters for wearable electronics and biomedical devices," *Advanced Materials Technologies,* vol. 6, no. 3, p. 2000771, 2021.
[12] R. H. Baughman, A. A. Zakhidov, and W. A. De Heer, "Carbon nanotubes--the route toward applications," *science,* vol. 297, no. 5582, pp. 787-792, 2002.
[13] J. Robertson, "Realistic applications of CNTs," *Materials Today,* vol. 7, no. 10, pp. 46-52, 2004/10/01/ 2004, doi: https://doi.org/10.1016/S1369-7021(04)00448-1.
[14] S. Jiang *et al.*, "Ultrahigh-performance transparent conductive films of carbon-welded isolated single-wall carbon nanotubes," *Science advances,* vol. 4, no. 5, p. eaap9264, 2018.
[15] R. Fornari, *Comprehensive semiconductor science and technology*. Elsevier, 2024.
[16] P. Prakash, K. Mohana Sundaram, and M. Anto Bennet, "A review on carbon nanotube field effect transistors (CNTFETs) for ultra-low power applications," *Renewable and Sustainable Energy Reviews,* vol. 89, pp. 194-203, 2018/06/01/ 2018, doi: https://doi.org/10.1016/j.rser.2018.03.021.
[17] M. M. Shulaker *et al.*, "Three-dimensional integration of nanotechnologies for computing and data storage on a single chip," *Nature,* vol. 547, no. 7661, pp. 74-78, 2017.
[18] S. K. Sinha and S. Chaudhury, "Advantage of CNTFET characteristics over MOSFET to reduce leakage power," in *2014 2nd international conference on devices, circuits and systems (ICDCS)*, 2014: IEEE, pp. 1-5.
[19] Y. P. Tsividis, "Integrated continuous-time filter design/spl minus/an overview," *IEEE Journal of Solid-State Circuits,* vol. 29, no. 3, pp. 166-176, 1994.
[20] S. Usui and I. Amidror, "Digital low-pass differentiation for biological signal processing," *IEEE Transactions on Biomedical Engineering,* no. 10, pp. 686-693, 2007.
[21] M. Raza, I. A. Khan, and M. Nizamuddin, "Design and Simulation of Pure CNTFET-OTA-Based Low-Pass Filters," in *International Conference on Nanotechnology: Opportunities and Challenges*, 2022: Springer, pp. 137-142.

DOI: 10.17148/IJIREEICE.2025.13815

[22] J. Deng and H.-S. P. Wong, "A compact SPICE model for carbon-nanotube field-effect transistors including nonidealities and its application—Part I: Model of the intrinsic channel region," *IEEE Transactions on Electron Devices,* vol. 54, no. 12, pp. 3186-3194, 2007.
[23] S. Jogad, N. Afzal, and S. A. Loan, "Design, Simulation and Comparative Evaluation of Active Filters Using 32-nm CNTFET-OTA," in *2020 International Conference on Emerging Trends in Information Technology and Engineering (ic-ETITE)*, 2020: IEEE, pp. 1-6.
[24] M. Cen, S. Song, and C. Cai, "A high performance CNFET-based operational transconductance amplifier and its applications," *Analog Integrated Circuits and Signal Processing,* vol. 91, pp. 463-472, 2017.
[25] S. M. A. Zanjani, M. Dousti, and M. Dolatshahi, "A new low-power, universal, multi-mode Gm-C filter in CNTFET technology," *Microelectronics Journal,* vol. 90, pp. 342-352, 2019.
[26] D. Thakur, K. Sharma, and R. Sharma, "Ultra low-power low-pass filter design for wearable biomedical applications," in *2021 Devices for Integrated Circuit (DevIC)*, 2021: IEEE, pp. 629-632.
[27] W. M. E. A. W. Jusoh and S. H. Ruslan, "Design and analysis of current mirror OTA in 45 nm and 90 nm CMOS technology for bio-medical application," *Bulletin of Electrical Engineering and Informatics,* vol. 9, no. 1, pp. 221-228, 2020.
[28] A. Azab, A. Onsy, and M. El-Mahlawi, "Monitoring of upper-limb EMG signal activities using a low cost system: Towards a power-assist robotic arm," *International journal of COMADEM,* vol. 18, no. 3, pp. 33-36, 2015.
[29] R. Kher, "Signal processing techniques for removing noise from ECG signals," *J. Biomed. Eng. Res,* vol. 3, no. 101, pp. 1-9, 2019.
[30] D.-G. I. Stănescu, P.-M. T. Nicolae, A.-G. I. Dobroiu, and L.-D. D. Popa, "Designing and testing of a second order active RC low-pass filter with different quality factors," in *2014 International Symposium on Fundamentals of Electrical Engineering (ISFEE)*, 2014: IEEE, pp. 1-4.
[31] M. Kumngern, N. Aupithak, F. Khateb, and T. Kulej, "0.5 V fifth-order Butterworth low-pass filter using multiple-input OTA for ECG applications," *Sensors,* vol. 20, no. 24, p. 7343, 2020.
[32] S. Sinha, G. Yeric, V. Chandra, B. Cline, and Y. Cao, "Exploring sub-20nm FinFET design with predictive technology models," in *Proceedings of the 49th Annual Design Automation Conference*, 2012, pp. 283-288.
[33] M. T. Bohr and I. A. Young, "CMOS scaling trends and beyond," *Ieee Micro,* vol. 37, no. 6, pp. 20-29, 2017.
[34] U. o. Minnesota. "Research CNTFET-based Circuit." https://mec.umn.edu/research (accessed 06 August 2025, 2025).
[35] S. Jogad, N. Afzal, and S. A. Loan, "Design and Simulation of Resistor Less Active Filter Using 22-nm CNTFET-Current Conveyor-II," in *2019 IEEE International WIE Conference on Electrical and Computer Engineering (WIECON-ECE)*, 2019: IEEE, pp. 1-5.