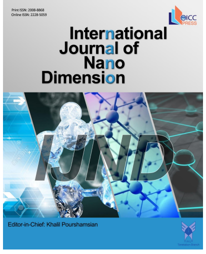

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Design a low-power low-pass nano dimension based filter with high linearity for next-generation WSN

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Abstract:

Wireless Sensor Networks (WSN) has received a lot of attention from around the world in the past year due to its broad application in the military, industrial, environmental sense, and other areas. WSNs are a crucial component of the Internet of Things (IoT) ecosystem. As the IoT continues to grow, WSNs will play a vital role in collecting real-time data from sensors and transmitting it for analysis and decision-making. WSNs will enable smart cities, industrial automation, environmental monitoring, healthcare systems, and more.2.4 GHz, 868 MHz, and 433 MHz are some examples of the low radio frequencies that WSN frequently use to operate. Researching and developing RF transceiver chips for the WSN system is very important. Low Pass Filters (LPF) a crucial component of the wireless sensor network chip will have a direct impact on the system as a whole. In WSNs, LPF can help to increase data transmission reliability and efficiency, especially when numerous nodes are transmitting data at once. However, the passive forms of LPFs in contemporary devices suffer greatly from a number of problems, including poor quality components, a limited ability to tune, undesirable harmonic interference, and a huge die size. Instead, some of these constraints can be overcome by active low pass filter types. Therefore, this research presents current-mode LC-ladder filter with improved linearity and dynamic range. We have taken 130 nm RF CMOS technology node at 1.2 V process to simulate LC-ladder filter using ADS Tool from Keysight. For improving the linearity of the LPF, OTA is also proposed with high output voltage swing and classical filter topology's transconductor are rewired. By combining each method filter demonstrates better results in terms of linearity that is P1dB -30 dBm and IIP3 20 dB with dynamic range greater than 56 dBm.

Keywords: Analog filter; Linearity; Low-power; LPF; Nano dimension; Operational transconductance amplifier (OTA); WSN

1. Introduction

As information technology advances quickly, more bandwidth is needed to transport multimedia data. Integrating wideband wireless front-ends into local communication networks that are appropriate for these uses presents significant problems given the shift to wireless communication networks. The Wireless Sensor Network, also known as WSN is a self-organizing system made up of numerous sensors that is designed to collect, process, and transmit data. Numerous fields, including military service, medical treatment, science of the environment, industrial monitoring, and others, make extensive use of the WSN [1]. A new perspective in wireless communications is represented by Wireless Sensor Networks at mm-wave. The described frequency range of mm-wave, which is between 30 GHz and 300 GHz, is a potential future frequency range [2]. Many small microsensor nodes make up a wireless sensor network, which is a multi-hop adhoc network created by wireless communication system to gather and process data in the network's coverage area and deliver to observers. WSN has received a lot of attention from around the world in the past year due to its broad application in military operations, industrial, environmental sense, and other areas. The use of Wireless Sensor Networks (WSNs) at higher frequencies such as 120 GHz is gaining interest for high-speed wireless internet-of-things (IoT) applications with short ranges. This is due to the potential advantages of higher frequencies, including wider available bandwidths and smaller antenna sizes [3]. Wireless Sensor Networks (WSNs) are expected to play a crucial role in the Internet of Things (IoT) ecosystem. With the increasing demand for connected devices and the ability to collect and analyze data in real-time, WSNs are becoming a key enabling technology for IoT applications.

WSNs can be used to monitor a variety of physical parameters such as temperature, humidity, pressure, and motion, and transmit this data wirelessly to a central hub or server for further analysis. This allows for real-time monitoring and control of various systems and processes, such as building automation, environmental monitoring, and industrial control. More autonomous, thought-provoking, and intelligent WSNs that can decide for them are something we can predict. The IEEE 802.15.4 standard specifies 2.4 GHz as the WSN standard frequency. The 2.4 GHz frequency spectrum is accessible worldwide and subject to national regulatory agencies' control. The research and development of RF transceiver chips for the WSN system is very important. The goal of designing WSN both software and hardware was to use low power technologies. The efficiency and power consumption of the RF transceiver, a crucial component of the wireless sensor network chip, will directly impact the system as a whole. Designing Radio Frequency Integrated Circuits (RFICs) involves several trade-offs that need to be carefully considered to achieve optimal performance. Some of the most important trade-offs include: Power consumption vs. performance: RFICs often operate on battery power, and power consumption is a critical factor in determining the battery life of the device. However, reducing power consumption can come at the cost of reduced performance, such as lower sensitivity or lower signal-to-noise ratio.

Size vs. performance: RFICs need to be small enough to fit within the device or system they are intended for, but reducing the size can come at the cost of reduced performance. For example, a smaller antenna may have lower gain or reduced bandwidth compared to a larger antenna. Cost vs. performance: The cost of manufacturing an RFIC can be a significant factor in the design process. Reducing the cost can come at the cost of reduced performance or additional design complexity. Linearity vs. power efficiency: RFICs need to operate in a linear range to minimize distortion in the signal. However, linear operation can come at the cost of reduced power efficiency, as higher power consumption may be required to achieve linear operation. Noise vs. sensitivity: RFICs need to be designed to minimize noise to achieve high sensitivity. However, reducing noise can come at the cost of increased power consumption or increased circuit complexity. Low pass filter has the ability to reduce noise and spikes in a digital-to-analog converter's output signal.There are several reasons why filtering is necessary in WSNs:

Noise reduction: The sensor signals in WSNs are often corrupted by noise from various sources, such as environmental factors, sensor imperfections, and interference from other wireless devices. Filtering can be used to remove this noise and improve the accuracy of the measurements. Signal conditioning: Filtering can be used to condition the sensor signals to match the requirements of the application.Data compression: WSNs generate a large amount of data, which can be expensive to transmit and store. Filtering can be used to reduce the amount of data generated by the sensors by removing redundant or irrelevant information, which can help to reduce the energy consumption of the network and increase its lifetime. Interference rejection: WSNs often operate in noisy and interference-prone environments, which can cause errors in the sensor signals. Filtering can be used to reject interference from other wireless devices and improve the reliability of the network.

When designing a ladder filter for a Wireless Sensor Network (WSN), some key specifications to consider include operating frequency range: The filter should be designed to operate within the frequency range of the WSN application. Insertion loss: This refers to the amount of signal power that is lost as it passes through the filter. The insertion loss should be minimized to ensure that the filtered signal is as strong as possible. Passband ripple: This refers to the variation in signal amplitude within the passband of the filter. The passband ripple should be minimized to ensure that the filtered signal has a consistent amplitude. Stopband attenuation: This refers to the amount of signal power that is attenuated in the stopband of the filter. The stopband attenuation should be high to ensure that any unwanted signals outside of the passband are attenuated as much as possible. Linearityrefers to its ability to faithfully preserve the input signal's shape and amplitude without introducing distortion. Impedance matching: The filter should be designed to match the impedance of the WSN application, to ensure maximum power transfer between the filter and the rest of the circuit. Physical size: The filter should be designed to fit within the physical constraints of the WSN application, while still meeting the desired specifications. All wireless front-ends fundamentally require RF filtering, which is also one of the most challenging components to integrate. This has been a significant barrier to the adoption of integrated wireless terminals with low power and cheap cost. It is frequently required in wideband wireless applications that a receiver chain's frequency response for in-band transmissions be flat. The receiver must also be able to suppress interfering out-of-band signals and adjacent channels to a low enough level so that they don't lower the receiver's bit error rate. A tiny passband ripple selective analogue baseband filter is required, especially in direct-conversion and low-IF receivers.

2. Materials and methods

Wireless Sensor Networks (WSNs) have been used for applications requiring low data rates and low energy consumption. The design of a front-end receiver as shown in Figure 1 depends on various factors, including the specific communication standard, desired performance specifications, frequency range, and noise environment. It is crucial to optimize the front-end receiver for sensitivity, selectivity, and dynamic range to ensure efficient signal reception and maximize the system's overall performance.

In a WSN, LPF is a key component. LPFs are commonly

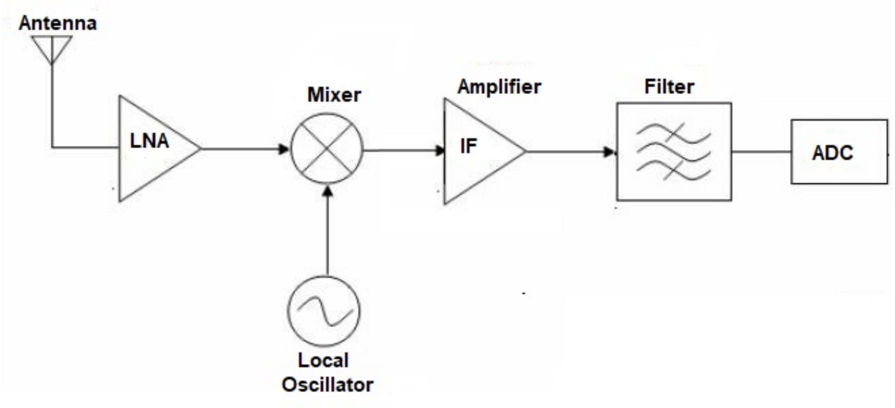

Figure 1. Block diagram of receiver front end.

used to filter out high-frequency noise, interference, and harmonics from the signals generated by the sensors. This helps to improve the accuracy and reliability of the data collected by the WSN, by reducing the impact of unwanted signals on the measurement and communication of data. Even while filters used in WSNs are significant, there are still several research gaps in the field. Some potential research gaps in the implementation of LPFs for WSNs include:

a) Filter performance and power consumption trade-offs: In a WSN, power consumption is a critical design consideration due to the limited energy resources of the network nodes. Therefore, there is a need to optimize the filter performance in terms of bandwidth, selectivity, and attenuation, while minimizing the power consumption of the filter circuit.

b) Linearity of LPF: A non-linear filter can introduce distortion, inter-modulation, and harmonics in the filtered signal, which can degrade the signal quality and reduce the performance of the network. A linear LPF, on the other hand, preserves the signal's shape and amplitude and reduces the noise and interference in the received signal. This improves the signal-to-noise ratio (SNR) and increases the sensitivity and accuracy of the sensing or communication system.

c) Dynamic range: The dynamic range of an LPF in WSN is important because it determines the range of signal levels that the filter can handle without distortion. In WSNs, the dynamic range of LPFs is critical because the signals received by the nodes can vary widely in amplitude, depending on the distance from the source, the strength of the transmitter, and the nature of the signal itself. New design strategies that can increase the linearity of filters while keeping their low power consumption require more study. Integration with additional RF front-end parts One element of the RF front-end of a WSN transceiver is a low pass filter. Additional research is required to determine how low pass filter might be used with other devices, such as low-noise amplifiers, mixers, and oscillators, to enhance the RF front-end's overall performance.

d) Adaptability with various wireless technologies: WSNs can utilize many wireless technologies, including WiFi, Bluetooth, and Zigbee, each of which has specific RF frontend requirements. Further investigation is required to determine how LPF can be created to be consistent with these many standards while preserving their excellent performance and low power consumption.

e) Impact of environmental factors on filter performance or sensitivity: WSNs are often deployed in harsh and unpredictable environments, which can impact the performance of the LPF. Factors such as temperature, humidity, and electromagnetic interference can affect the filter's attenuation and selectivity, and may require additional design considerations. Even if some recent research efforts have done a great work in this area. A Low Pass Filter creation and execution could be improved by addressing these research gaps.

Compared to discrete time filters, continuous time (CT) filters are simple, low power, and noise-free, and they have many uses in communication, measurements, and instrumentation. Lower bandwidth for greater gains is one of the drawbacks of the standard voltage mode circuits and filters realized using operational amplifiers. The advantages of current-mode circuits over voltage mode circuits, however, include larger bandwidth, increased linearity, and lower power consumption [4–7]. The usage of each filter topology in radio frequency integrated applications is constrained by one or more limitations. The continuous-time filters based on active RC integrators [8] have limited high frequency operation because of the finite gain-bandwidth product of the op-amps employed in feedback, in contrast to SC filters that have a switching clock signal leaks into the filter output, causing unwanted harmonic distortion [9]. The Q-enhanced LC and Gm-C filters have proven to be the most effective for use above gigahertz frequencies among all filter topologies [10–13]. Integrating LC filters at RF frequencies is challenging due to several reasons at RF frequencies, the size and weight of these components become a significant challenge for integration into a compact and lightweight system, lower dynamic range, tuning problems, etc [14].

Utilizing two popular methods, lossless doubly terminated LC ladder realization and cascaded biquads, higher order CT filters are created. According to a vast literature, the lossless doubly terminated LC ladder approach is often recommended [15–20], compared to cascaded biquads, this method yields component variation-tolerant filter realizations, significantly higher dynamic range performance. The use of inductors is the only drawback of this approach, as their integration into an integrated circuit (IC) would be impractical in terms of cost, tunability, and space utilization. Either the element replacement method or the leap frog method can be used to overcome these shortcomings. Gyrators are used in place of inductors in the element replacement method. This approach is only appropriate for grounded inductor-based devices because it is difficult to make high-quality floating inductors. Another technique for replacing elements is the use of FDNR, which works well for creating low pass filters. In the leap frog method, the interaction between multiple passive elements is simulated using a signal flow graph (SFG) methodology. Then, employing lossy and lossless active integrators, these SFGs are physically realized. The filters that result from this process are known as active LC-ladder filters [21–26].

In addition to having a wider bandwidth than active-RC filters [27] GmC filters also operate less linearly when feedback amplifiers are not present [28, 29]. Recent technologies have made the linearity issue with GmC filters worse since they aggressively scale geometric sizes while also reducing the voltage supply by compromising the most crucial linearity measures. Many methods have been suggested to increase the linearity of GmC filters, most of which focus on circuit-level fixes to increase the linearity of the transconductor. There are various solutions to increase the linearity given in the literature mosfet operate in triode region [30], many different techniques like floating-gate [31], and cross-coupled cells [32, 33] also used master-slave automatic tuning and cancellation of the nonlinear terms [34–36]. However, the majority of the aforementioned techniques generate unavoidable trade-offs between the dynamic range and the power, area, and noise characteristics. Some solutions are not only proven to be incompatible with the limitations of nano-scale technology, but also increase the complexity of the design. For front-end circuits in wireless transceivers and related applications to filter out out-of-band interferences with the least amount of distortion, excellent linearity performance is a need. Due to this, we introduce in this study a methodical design technique in order to improve the linearity we will also consider other key points. Figure 2 shows the relation between input power and output power which further relates DR (Dynamic range) [37].

The linearity of the transconductor as well as the voltage swing at their input affect the linearity of the conventional ladder-type filter. Therefore, a number of methods have been put up in order to realize the linear transconductor that was briefly discussed. Instead, we will concentrate on the input voltage swing of the transconductor in this Section and invent a different model of a ladder-type GmC filter that has fewer restrictions on the linearity of the intermediate stages. For WSN selectivity is also an important parameter to increase the selectivity of an active filter increase the order of the filter. However, increasing the order of the filter also increases its complexity and can lead to higher component costs. A higher-Q active element such as a gyrator or a state-variable filter can help to increase the selectivity of the filter.

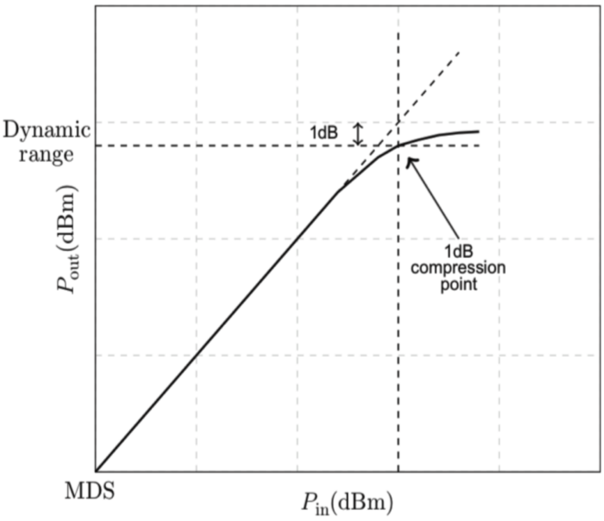

Figure 2. Dynamic range of a filter. [35]

3. Implementation of proposed low pass filter

Typically, distributed or lumped circuit elements are used to implement filters. As the size of the electrical component are comparable to the signal wavelength, filters developed above 1 GHz employing lumped parts produced disperse effects. In general, Butterworth or Chebyshev filters may be utilized for RF applications. The choice of filter is further influenced by additional elements such desired rejection, high- or low-frequency rolloff, variation with phase, etc. Now, filters can be designed to have less harmonics to increase the linearity. Due to its complicated pole position, a simple LC structure has a suitable quality factor, and the ladder it creates works extremely well in radio frequency narrowband applications like WSN. Most passive filters have a ladder-like shape. Ladder passive filters, which have historically been the most studied in circuit theory, are renowned for being quite insensitive to changes in component values. Figure 3 below show the prototype of a doubly terminated 5^{th} order LC ladder structure for the desired frequency of 2.4 GHz. The value of capacitances in shunt has been normalized to a standard range and chosen keeping in mind the technology at hand for implementation (130 nm RF-CMOS).

The values are $C_1 = C_5 = 2.8643$ pF, $L_2 = L_4 = 4.287$ nH and $C_3 = 4.4648$ pF.

3.1 Inductor emulation

A different, more straightforward way to create an LC filter is by using active inductors, also known as gyrators, in place of passive ones. Two transconductor connected back to back are the simplest way to conceptualize a gyrator Figure 4. When a gyrator-C network's transconductor input and output impedances are infinite and its transconductances are constant, the network is said to be lossless. It is necessary to create a tested inductor emulation methodology, which is described below. It necessitates the design and deployment of an effective transconductor (Gm). As a result, the grounded inductor is implemented in the diagram as Zin determines the inductive reactance values for the selected

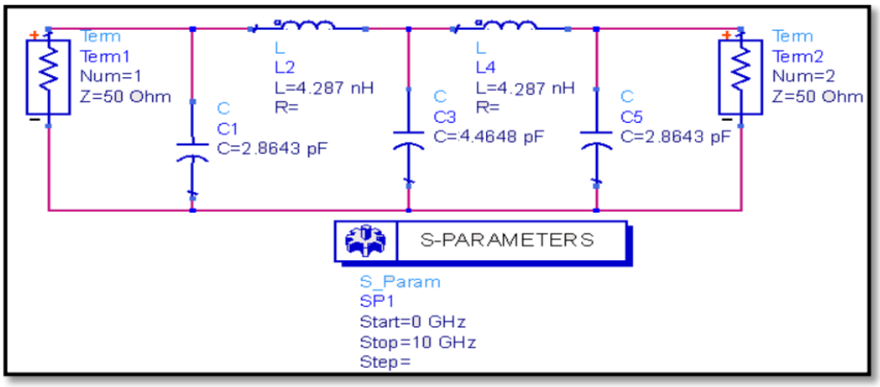

Figure 3. Circuit of Low Pass Filter (Prototype).

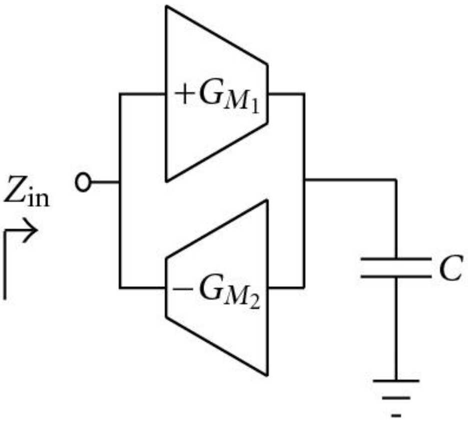

Figure 4. Gyrator using OTA.

Gm and capacitance combinations.

3.2 Proposed OTA and filter implementation

No matter how the filter is implemented, the linearity can be increased by limiting itself to circuit-level fixes that increase the linearity of the transconductor [38]. These methods can be applied to the proposed filter. Gain increased current mirroring [39, 40] and self cascoding [41] are combined in the suggested OTA. In the proposed OTA, the two approaches enable a very large DC gain. The proposed OTA is designed based on a 130 nm CMOS with 1.2 V supply. Gain can be increased by increasing the number of transistors as shown in Figure 5. Aspect ratio for proposed OTA has been given in Table 1. In the given Figure 6 proposed implementation has been shown in this all the inductors have been replaced by transconductor. The transconductor are connected in different manner to improvise the linearity of the filter. The linearity of the proposed filter not only depends on the large voltage swing but also depends on linearity of transconductor stages.

4. Results and discussion

Simulation results for ladder based GmC lowpass filter designed for wireless sensor network are discussed in this section. The above mentioned 5^{th} order low pass filter has been simulated using ADS tool using 130 nm CMOS technology. This filter based on replacement of bulky passive devices with active, for that purpose a high linear transconductor is simulated. Figure 7 shows a high gain of proposed OTA i.e 78 dB with phase margin of 500 using 1.2 V power supply.

Figure 8 shows high output voltage swing of 700 mV with power dissipation of 800 nW. Figure 9 shows the simulation result of low pass filter. Filter is designed for 2.4 GHz and marker in the graph shows the cut of frequency of 2.412 GHz which is as sharp as desired. The value of S (1,1) is 2.89. It is a

reflection coefficient that quantifies the amount of power reflected back towards the source from a device or component. It is used to evaluate impedance matching and assess

Table 1. Parameters of the OTA transistors.

Transistors	Transistor size(W/L)
M_1-M_2	16μ/250n
M_3-M_4	16μ/250n
M_5-M_6	12μ/250n
M_7-M_{10}	10μ/250n
M_{11}-M_{16}	8μ/250n

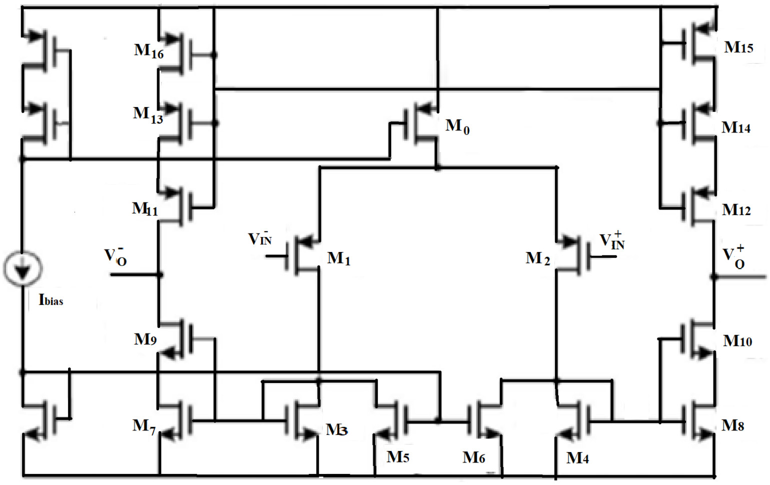

Figure 5. Schematic diagram of proposed OTA

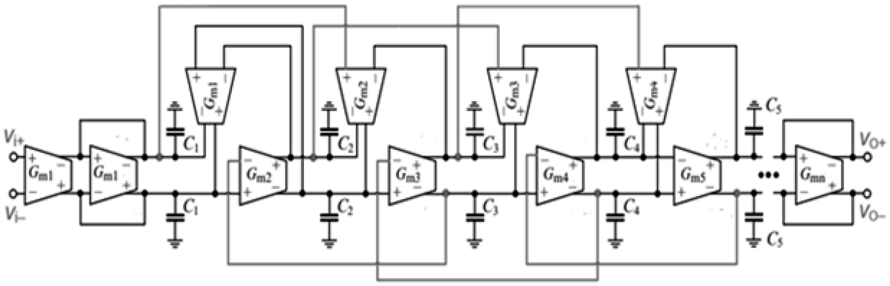

Figure 6. Ladder based Gm-C filter.

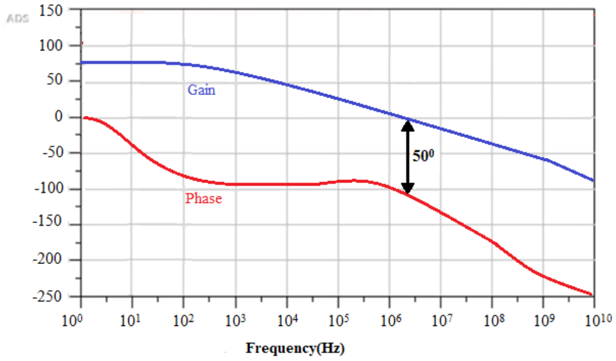

Figure 7. Simulation result for OTA gain.

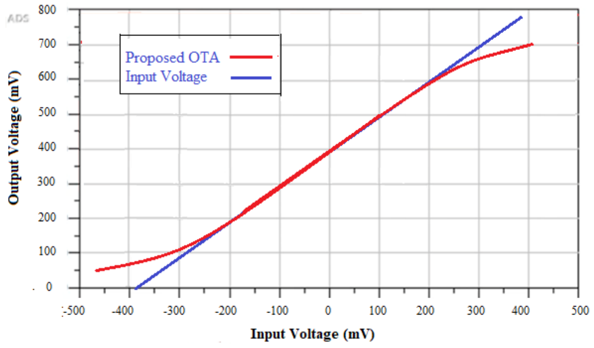

Figure 8. Linear characteristic of OTA.

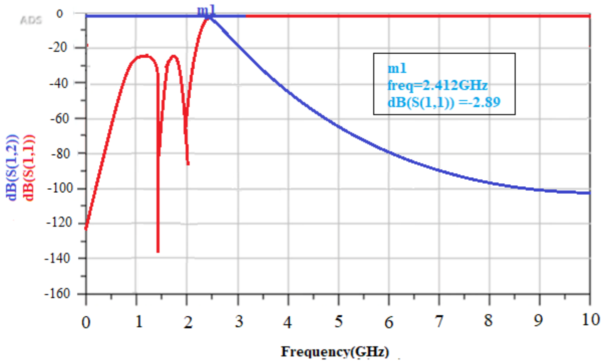

Figure 9. Low Pass Filter frequency response.

the effectiveness of power transfer in microwave and RF systems. A low value of |S11| indicates a good impedance match and minimal power reflection. Figure 10, 11 shows the performance of linearity of the filter Figure 10 shows 1 dB compression point and Figure 11 showsthird order intercept point IIP3. When the input power exceeds the 1 dB compression point, the circuit starts to exhibit nonlinear behavior. Simulation shows P1 (dB) is −30 dbm. IIP3, or the third-order input intercept point, is a parameter used in RF and microwave systems to characterize the linearity and distortion performance of the filter. Figure 11 demonstrates the value of IIP3 is 20 dBm. A higher IIP3 indicates a device with better linearity and lower distortion. Regarding

Table 2. Comparative analysis of various technologies

Reference	Technology (nm)	Topology	Filter Order	Supply Voltage V	Bandwidth	Linearity IIP3	Power
[40] 2023	65	GmC LPF	5	1	1	9.4	0.167 mw
[25] 2021	40	GmC LPF	3	1.1	20 – 80 M	7.67	1.94-2.27 mW
[39] 2021	90	LPF		1.3	35.48		1.56 mW
[12] 2019	28	GmC LPF	3	1	-	16	0.9 mW
[40] 2016	180	GmC LPF	4	1.8	-	2.59 – 4.14	10.27-12.96 mW
[41] 2013	180	GmC LPF	3	0.9	>1	10.75	411.6 μW
Proposed work	130	GmC LPF	5	1.2	-	20	1.48 mW

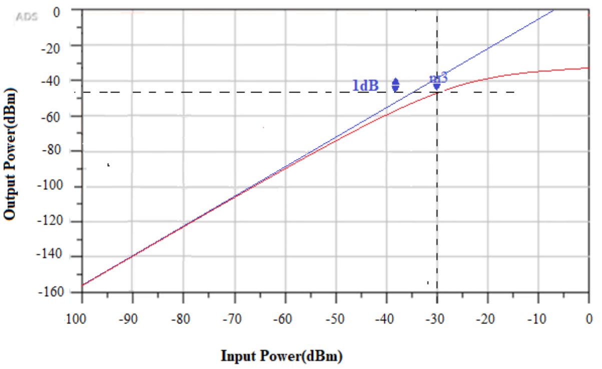

Figure 10. Simulation for 1 dB compression point.

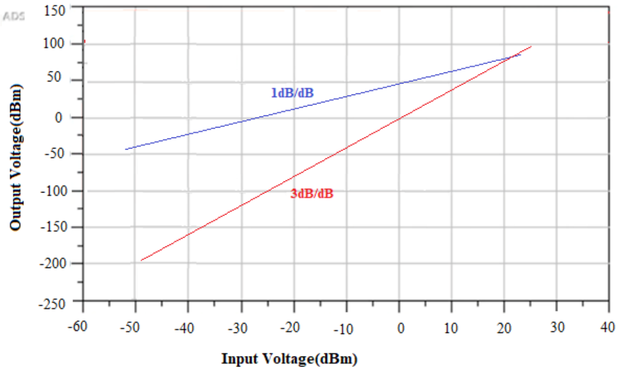

Figure 11. Simulations for third intercept point.

WSN all the values are acceptable. Comparison has been done in Table 2 with some latest research works.

5. Conclusion

For the next generation 6G spectrum range, the ladder based low pass filter has been designed in this research article for WSN technologies to operate at 2.4 GHz frequency where the input RF frequency is close to 122.4 GHz. The simulation has been done by using ADS simulation tool. As per the protocol IEEE 802.15.4 for WSN design parameters has been adopted for providing better results in terms of better linearity, better harmonic cancellation, good dynamic range with low power usage to other filter types A different approach has been used to improve the linearity. An element replacement method was used for implementing 5^{th} order ladder type GmC low pass filter. For that a simple architecture OTA has been proposed including gain increasing and cascading methods. By increasing number of transistors gain of OTA can be increased. Proposed OTA has a gain of 78 dB with 700 mV output voltage swing which demonstrates high linearity. For implementing 5^{th} order ladder filter OTAs are rewired to improve the linearity. This design shows the good performance and can be used for high linear, low power designs. Fifth order Gm-C based ladder type low pass filter shows cut off frequency 2.412 GHz with intercept point IIP3 21.6 dBm and dynamic range greater than 56 dBm with 1.48 mW power dissipation all of which shows great improvement in terms of linearity with respect to other works performed in this field. The proposed method depends on the linearity of transconconductors and how they are connected in ladder type filter. WSN may become a prominent factor in wireless communications in the future with more research and development. It has the potential to significantly improve WSNs' capabilities for a variety of IOT-based applications, such as smart cities, healthcare, and environmental monitoring.

Authors Contributions
All authors have contributed equally to prepare the paper.

Availability of Data and Materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work

reported in this paper.

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