Analog Cochlea Filter using FINFET

Parvathy Raju
PG Scholar
Applied Electronics and Instrumentation
Younus College Of Engineering and Technology
Kollam, India

Anju Iqubal
Associate Professor
Electronics And Communication Engineering
Younus College Of Engineering and Technology
Kollam, India

***Abstract*—This paper mainly presents the design of cochlea filter using FINFET. There are mainly three specialized stages using floating active inductors which provide passive response in lower frequencies, active tunable response in mid-band frequencies and ultra-steep roll-off at transition frequencies from pass-band to stop-band. FinFET devices has higher controllability, reduced short channel effects (SCEs), higher trans-conductance, and ideal sub threshold voltage. By replacing CMOS by FINFET results in increased operational speed and reduces device area.**

***Keywords*—Analog VLSI; CMOS Cochlea; Floating Active Inductor; FinFET**

I. INTRODUCTION

There are many studies related to the implementation of silicon cochlea in analog VLSI which are mostly driven by the increasing demand for high performance and power efficient auditory processing chips in biomedical applications as well as in portable consumer electronics. An essential building block of a silicon cochlea is the filters, as input signal has to be separated into multiple frequency channels [1]. The signal separation is achieved through cascade filtering structure. The frequency response of the filters must be highly adjustable so that to achieve the active gain adaption and sharp tuning observed in biological cochlea [1]-[2].

The parallel filter bank structure is used to avoid issues like noise accumulation and linear range limitation in cascade structure. It has each channel contains one band-pass filter, which struggles to achieve the similar level of tunability as well as a stop band cut-off steepness compared with the cascade structure. The OZGF is a variant of the well-known Gammatone Filter (GTF) proposed by Johannesma in 1972 and was introduced by Lyon in 1996 as an efficient auditory filter in terms of both its relative ease of implementation and its simple mathematical parameterization which consists of four sections of biquads cascaded together to achieve reasonable biological fidelity [3].Two dimensional topology has bio-inspired approach with addition of coupling effects between frequency channels so that to seek better system performance.

A floating active inductor is used in weak inversion of CMOS transistors. CMOS spiral inductors has a broad range of applications in high-speed analog signal processing and data communications. But integrated spiral inductors have a number of limitations due to their layouts. These limitations are low quality factor, low self-resonance frequency, small as well as a non tunable inductance and need for very large silicon area. Implementation of inductors with active elements offers certain attractive advantages over their spiral counterparts including large and tunable inductance and low silicon consumption [2], [4]. With the three classes of filters cascaded together, a biomimetic analog cochlea filter channel is built.

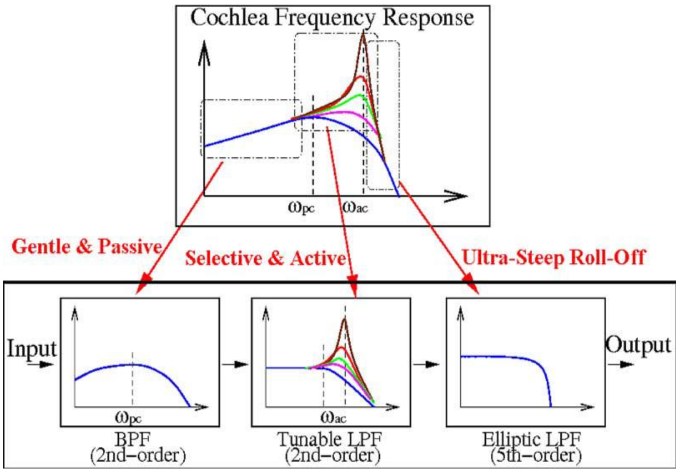


Fig. 1. System architecture. Each of the three sub-filters emulates one stage of the biological cochlea frequency behavior.

In this work, a filter is designed to improve performance of existing CMOS filter channel which is superior to gammatone filter based design. Typical CMOS layout techniques involve transistors with a single gate. In the traditional approach for CMOS, compact layouts are realized by optimal transistor chaining of a number of p-type and n-type transistors. However, in the case of ambipolar gates, the polarity of the transistor (p-type or n-type) changes with the input signals. FinFET has reduced short channel effects (SCEs), higher trans-conductance, and ideal sub threshold voltage. Whereas FinFETs are ideal for digital applications, they will also be powerful competitors for linear radio frequency (RF) applications such as wireless communication because of their capability to handle large amount of terahertz modulation. These circuits provide extra gains in terms of area, power and speed by using FinFET in independently driven mode because of its analog tunablility function [2], [9]. Therefore the two gates are separated and biased as compared to symmetrically driven mode counterparts of FinFETs used in digital applications. A wide tuning range of performance in the figures can be identified using identical or conjugate biasing of *n*-type and *p*-type FinFETs which are preferable for certain cases, and therefore, it can establish voltage tuning with high accuracy.

II. SYSTEM DESIGN

Fig.1 shows the system architecture of the proposed cochlea filter. Experiments shows magnitude and frequency response of the basilar membrane in biological cochlea has an asymmetric shape with highly active behavior. The response is gentle and passive in low frequencies, selective and active in mid-band frequencies and steep in the transition from pass-band to stop-band, which indicates the frequency response of cochlea can be divided into three classes of filters are cascaded together in the system having: A low-Q biquad band-pass filter mimics the flat and passive response of the biological cochlea at low frequency range, a tunable high-Q biquad low-pass filter mimics the selective and active behavior at the center frequency band, and a 5th -order elliptic filter provides the required sharp cutoff in the stop-band. With the three filters cascaded together, the cochlea filter as a whole is able to behave similar to a biological cochlea [1]-[2]. The cochlea filter in total is a 9th-order system.

III. CIRCUIT IMPLEMENTATION

A. Basic Cell:Floating Active Inductor(FAI)

Floating active inductors have been studied and designed for high-speed applications. CMOS spiral inductors has a broad range of applications in high-speed analog signal processing and data communications. But integrated spiral inductors have a number of limitations due to their layouts. These limitations are low quality factor, low self-resonance frequency, small as well as a non tunable inductance and need for very large silicon area. Implementation of inductors with active elements, offers several advantages over their spiral counterparts including large and tunable inductance and low power consumption [1]. Unfortunately active inductors have high level of noise due to a large number of transistors. Floating gyrator-C active inductors offer the following advantages over their single-ended counterparts: (i) The differential configuration of the transconductors effectively reject the common-mode disturbances of network, making them particularly able for applications where both analog and digital circuits are fabricated on the same substrate. (ii) The level of the voltage swing of floating active inductors is twice that of corresponding single-ended active inductors [2].

An improved FAI cell based on classical gyrator-C topology as shown in Fig. 2. The capability to tune the inductance value with a moderate Q-factor of FAI has been a great advantage for the designer rather than to use passive inductors like spiral and bonding wire as they exhibits fix inductance value, poor Q-factor and require large die area. The NMOS FINFET pair MN provides the positive trans conductance, while the PMOS FINFET pair MP provides the negative trans conductance [2]. The gyrating ports PA and PB are terminated with capacitive load $C_{gyrator}$. However PA (PB) is connected at the source of FINFET MP, which is a low impedance end, therefore an equivalent resistance of $1/g_{mp}$ exists in parallel with $C_{gyrator}$. On the other hand, another PMOS FINFET pair MX provides a negative resistance of $-1/g_{MX}$ at PA (PB).FAI works as a resistor in low frequency, as an inductor as well as a capacitor in high frequency. Based on the FAI cell, the three classes of filters are established. The FAI makes the cochlea filter implementation highly straightforward [9].

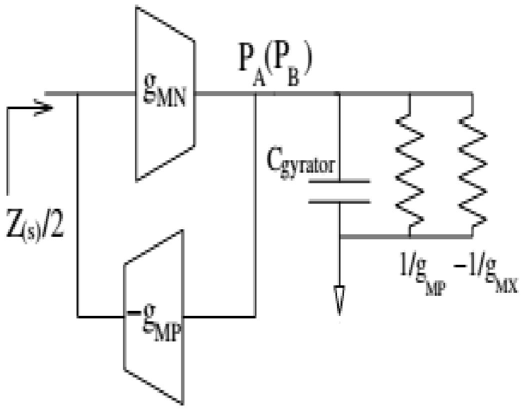


Fig. 2. FAI simplified model.

B. FINFET

The term FinFET was coined by Profs. Chenming Hu, Tsu-Jae King-Liu and Jeffrey Bokor, UC Berkeley researchers to explain a non-planar, double-gate electronic transistor developed on associate SOI substrate. The distinctive feature of the FinFET is that the conducting channel is wrapped by a slender semiconductor "fin” that forms the body of the device and the fin thickness determines the effective channel length of the device. A FinFET structure has been shown in Fig.3 which indicates the gate and channel arrangement between source and drain in FinFETs. A number of materials can be used to form substrate and channel. Here, Indium-phosphate combination has been used along with Indium-Gallium-Arsenide to form p-type substrate [9].

FINFETS are non-planar structures unlike planar CMOS structures built on a Silicon on Insulator(SOI). CMOS introduces noise and other adverse factors because of short channel effects and leakage when the length of gate is beyond 22nm causing a swing in threshold voltage. To replace this, a multigate device is used for a precise control over the current across the channel. FINFET as shown in Fig.4 has gate on three sides, where a CMOS has gate only on one side. Hence, these FETs are called multigate FINFETs. Intel FINFETs has a triangular structure as they increase switching speed [11]. FINFETs operate in two modes Independent Gate (IG) mode and Shorted Gate (SG) mode as shown in Fig 5. These modes decide upon how many gates are used to control the channel. If it’s an Independent mode, there are two gates to control the channel, and each gate terminals are separated. In the Shorted mode, both the gate just as CMOS has its own parasitic capacitance , due to gate-source and gate drain overlap, even a FINFET has its parasitic capacitance more than that of CMOS as the gate is covered in all 3 sides as shown in Fig.4. It also illustrates how source and drain is embossed on the insulator substrate and the gate covering the channel in all the three sides. This parasitic capacitance brings more noise to the device, making it adverse to be used in analog as well as mixed signal circuits [12].

Due to problems in aligning the front and back gates, as well as in building a low resistance to the back gate, DGFETs are difficult to fabricate. The FinFET has been developed to overcome the problems faced by DGFET. The structure of a FinFET with a cut-plane view is shown in Fig 5.

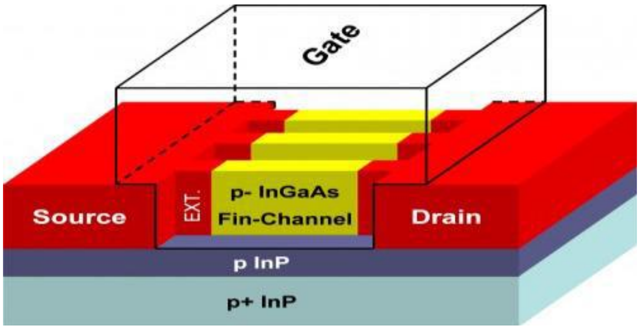


Fig. 3. FinFET structure.

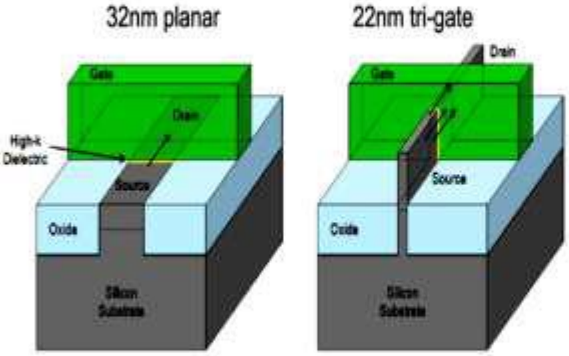


Fig. 4. CMOS vs. FINFET.

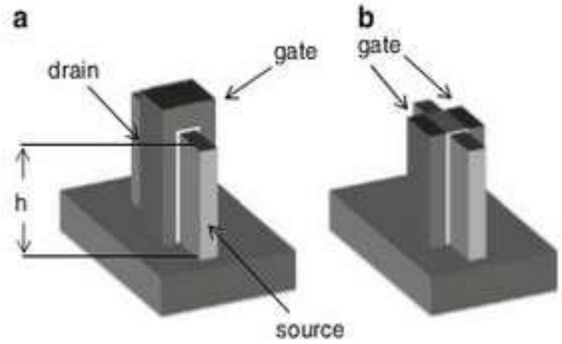


Fig. 5. (a) Shorted Gate FINFET (b) Independent Gate FINFET.

The FinFET is a promising device which is considered to be a suitable successor of DGFET, while it is probable too to be made using a high-*k* gate dielectric and a metal gate. The structure of a FinFET is shown in Fig 6(a). It is called so because of the thin channel region stands vertically similar to the fin of a sandwich between the source and drain regions. The gate covers around the body from three sides and thus reduces short channel effects (SCEs) [13], [14]. In strong inversion, conduction mainly arises along the sidewalls, whereas in sub threshold it arises along the fin centre. A structured FinFET is actually a device in which 3D effects play a non negligible role (whereas reasonable mean that the fin height is higher but not considerably higher than the fin width). Hence it is expected to focus on the 2D feature of the FinFET while developing a compact model. In other words, the fin height is assumed to be infinite. Thus all values derived in the model are based on a per-unit-fin-height basis such as charges and currents make the device double gate MOSFET.

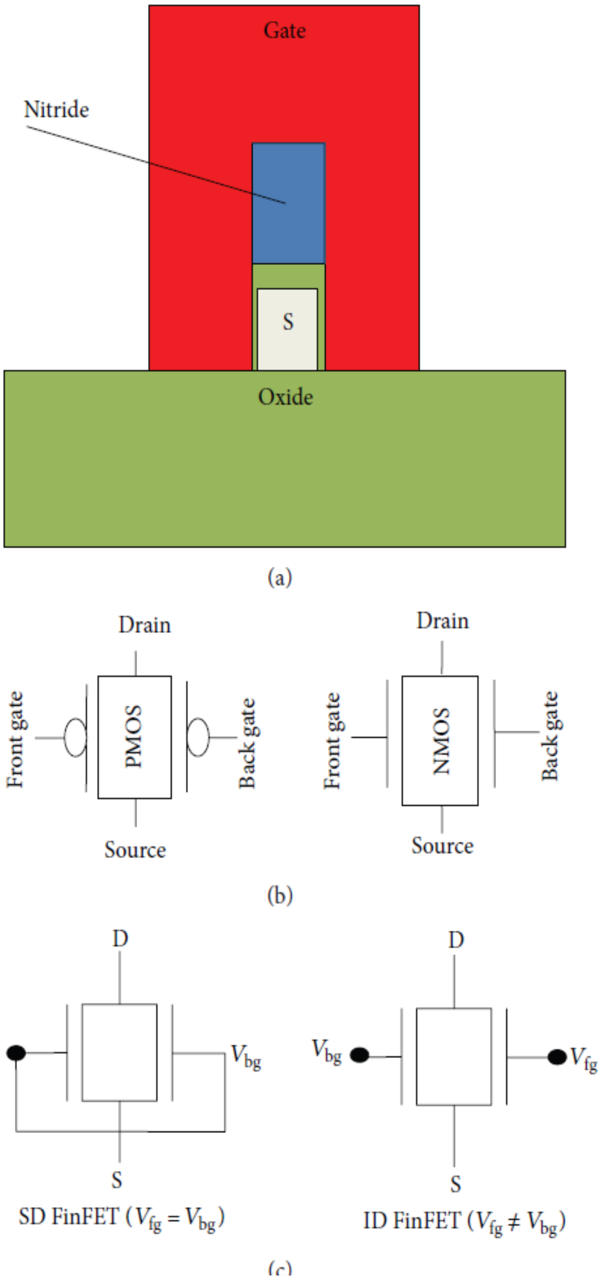


Fig. 6: (a) Double gate FinFET, (b) shows the FinFET circuit symbols, and (c) the SD and ID refer to symmetrically and independently driven FinFET.

The device being modeled is named as a double-gate MOSFET (DGFET) [11]-[14].

C. *Triple Stage Cochlear Filter Design Based On FAI*

a) Biquad Band Pass Filter: The low-Q biquad band-pass filter is implemented by loading a fully differential OTA with the FAI cell and a capacitor in parallel as shown in

Fig. 7.Gm represents fully differential OTA using FINFET. A low-Q biquad band-pass filter mimics the flat and passive response of the biological cochlea at low frequency range.Differential OTA is a source coupled pair of transistors. The sub-filters are built in balanced ladder topology using floating active inductors, which reduces the design complexity[1]-[2].

b) Biquad Low-pass Filter: The tunable high-Q biquad low-pass filter is implemented as a fully differential difference amplifier (FDDA) based buffer followed by an LC voltage divider, as shown in Fig. 8. A pair of FAI cells instead of a single one is used to build the LC voltage divider for three reasons. First, it keeps the circuits in fully differential configuration so as to minimize common-mode errors. Second, it allows the DC voltage across $C_{LP\ F}$ to approximate zero, so the output offset is minimized.A fully differential difference amplifier requires common mode feedback [2]-[4].

c) Sharp Cut-off Elliptic Filter: A 5th order elliptic filter is built to achieve sharp cut-off low-pass function as in Fig 9. The pair of OTAs at the input works equivalently as a source resistor. OTA is a differential voltage controlled current source (VCCS) where the output current is controlled by an applied input voltage signal [5]-[7]. This tunability is obtained by varying the trans conductance (g_m) of the OTA which in turn is controlled by bias current or voltage. However, tunability is restricted by the limited bandwidth of g_m, which depends on the bias current. OTA-based filters are composed of the open-loop OTA-C integrators where the devices are operated in the sub threshold region to realize a very low transconductances, typically the order of a few nano amperes. In OTA-based circuits, the bias current will dominate the performance of the filter circuit, and the ratio of capacitance to small trans conductance determines the time constant of OTA-C integrators [8], [10]. Using the FinFET, OTA has a better common mode rejection. The detailed cochlear structure is shown in Fig 10.

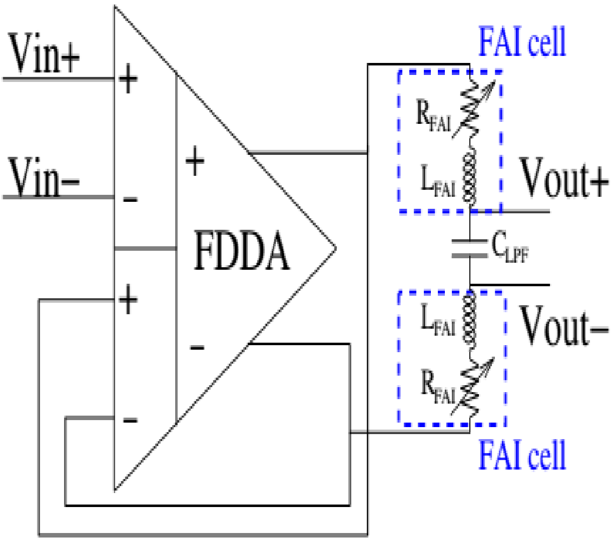
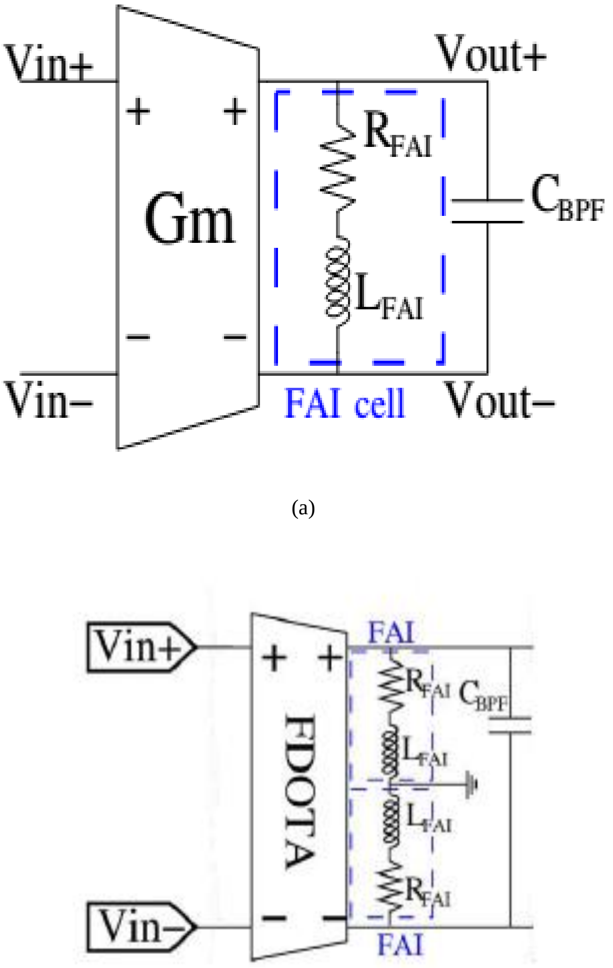


Fig. 8. Schematic of a tunable high-Q biquad LPF based on FAI.



(a)

(b)

Fig. 7(a),(b). Schematic of a low-Q biquad BPF based on FAI.

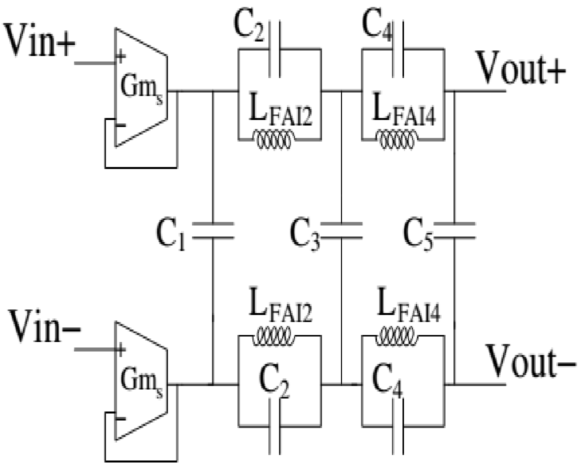


Fig. 9. Schematic of a 5th -order elliptic filter based on FAI.

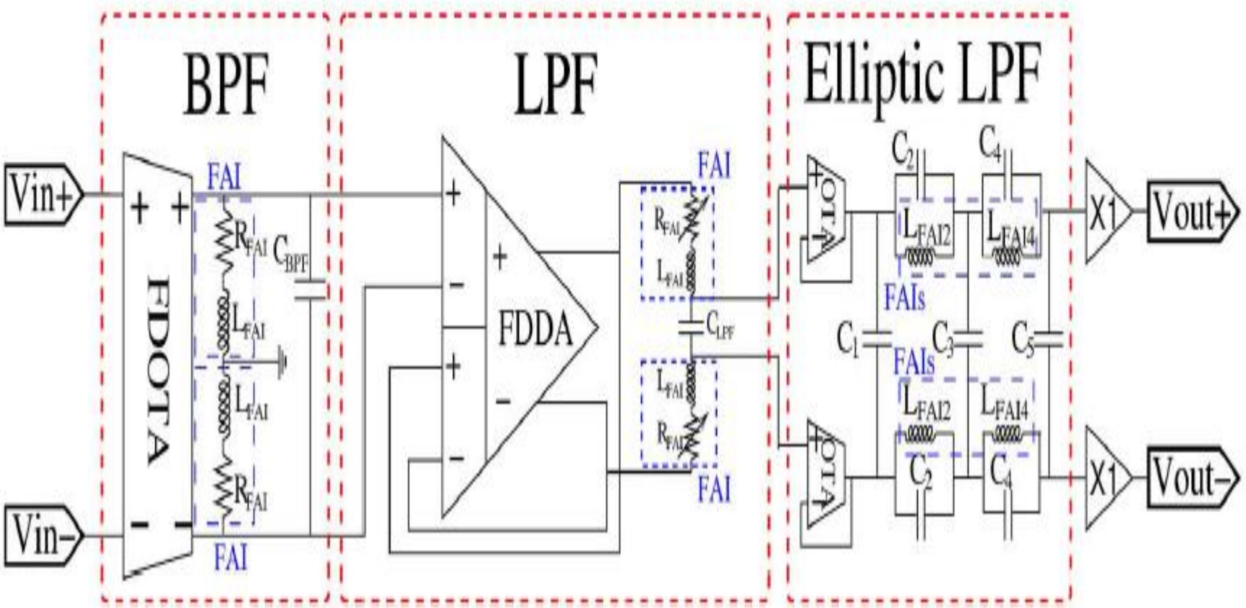


Fig.10. Detailed structure of the cochlear filter channel consisting of three sub-filters.

IV. CONCLUSION

In this paper an analog cochlear filter is presented using FINFET technology. Implementation of the cochlea filter is based on a basic circuit element, the FAI cell. As the FAI cell can be simply modeled as an inductor, the creation of the cochlea filter is made highly straightforward. Besides, the compact and floating features make it flexible for building different types of ladder LC topologies. A wide tuning range of performance can be identified using identical or conjugate biasing of *n*-type and *p*-type FinFETs which are preferable for most cases, and therefore, it can establish voltage tuning with high accuracy. Using the FinFET, OTA has a better common mode rejection [14]. FinFETs are extremely fast and power efficient devices, its disadvantage is being difficult to fabricate it to perfection, being a very small device and its series resistance and extrinsic parasitic capacitance high. They yielded considerable advancements in drain current, speed, threshold voltage, etc. Using FinFET instead of CMOS improves operational speed and reduces device area. In future we could implement this using CNFET instead of FinFET which reduces power consumption.

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