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Voltage Differencing Buffered Amplifier Realisation Using 32 nm FinFET Technology and Universal Filter Applications

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***Abstract*—This paper presents high-frequency universal filter applications based on a voltage differential buffered amplifier (VDBA) using 32 nm fin field effect transistor (FinFET) technology. FinFET technology is a promising alternative to complementary metal-oxide-semiconductor (CMOS) technology to avoid the problems caused by the decrease in transistor size as the technology evolves. In addition to the manufacturing process being similar to CMOS technology, FinFET technology offers many advantages, such as reduced short channel effects, higher drain current, reduced static leakage current, faster switching time, lower supply voltage, lower power consumption, and higher efficiency. The VDBA active circuit block, which has high input impedance and low output impedance, is preferred for high-frequency and high-bandwidth applications. It is advantageous to design active filter circuits using VDBA because of its superior features, such as lower power consumption, higher bandwidth, wider range linearity, and the ability to implement the proposed circuits without external resistors. In this study, FinFET-based VDBA and filter application are simulated with the Spice simulation programme using 32 nm PTM technology parameters. Simulation results using 32 nm FinFET technology are compared with those using 0.18 μm TSMC technology. It is concluded that 32 nm FinFET technology reduces power consumption by 98.8 % and increases bandwidth by 145 times. The successful results show that FinFET technology is superior to CMOS technology in analogue circuit design. FinFET-based VDBA circuits and filters will be more advantageous in the design of signal processing and biomedical applications.**

***Index Terms*—Voltage differencing buffered amplifier; Voltage-mode filter; FinFET; Universal filter.**

I. INTRODUCTION

As technology advances, more transistors must be placed on the same silicon area to meet the increasing demand for computing power. To increase transistor performance and accommodate more transistors, the length of the transistor channel must be reduced. This dimension has been gradually reduced from the past to the present, and the length has been reduced to nano dimensions. However, short-channel effects have recently pushed the limits of physics and engineering to the point where smaller transistors are no longer feasible. Conventional complementary metal-oxide-semiconductor (CMOS) technology has reached its physical limits [1], [2]. For these reasons, Moore's law has become challenging to sustain, and the focus has shifted to improving transistor efficiency and exploring new materials and elements. Since changing the manufacturing material is not economically viable, the next generation of transistors is of great importance in today's technology [3].

The fin field effect transistor (FinFET) was introduced in 2001 by Chenming Hu and his team to address problems caused by short-channel effects. These problems include leakage current, drain-induced barrier lowering (DIBL) subthreshold swing, and hot carrier effects that arise from the scaling of metal-oxide-semiconductor field-effect transistors (MOSFETs) to nano dimensions [4]–[7]. Often used by many researchers in circuit design applications, FinFET has been recognised as a promising alternative to solve the problems caused by short-channel effects that affect the operating performance of transistors and make transistors inoperable [8]. The main difference between the FinFET and MOSFET structures is that the channel between the drain and the source is wrapped with a thin silicon rib called a "fin" [9]. The three-dimensional structure provides better control of the electrical channel because it is controlled from multiple angles. This reduces leakage and prevents short-channel effects [10]. At the same time, FinFET is technically more straightforward to implement because the process is similar to CMOS technology. For this reason, many large companies have used it to produce small components [11]. FinFET has the advantages of scalability, effective channel control, reduction of short channel effects, higher drain current, reduction of static leakage current, faster switching time, lower supply voltage, lower power consumption, higher efficiency, and is more insensitive to software errors due to the nondoped channel. Due to all these advantages, the realisation of analogue and digital circuits with FinFET technology and CMOS technology gained speed [12], [13].

Active filter circuits are the basic building blocks of analogue signal processing applications. Active elements such as first-generation current conveyor (CCI) [14], second generation current conveyor (CCII) [15], current differencing

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transconductance amplifier (CDTA) [16], current differencing buffered amplifier (CDBA) [17], differential voltage current conveyor (DVCC) [18], voltage differencing buffered amplifier (VDBA) [19] are the basic block structures used in active filter circuits. The VDBA, which has high and low output impedances, isolates the input voltage from the output voltage while providing a high-voltage gain. The VDBA, which also has a differential input structure, is similar to a typical operational amplifier (OPAMP) in these features. It can process differential input signals without the need for an additional input resistor, unlike OPAMPs. They are preferred for high-frequency applications due to their wide bandwidth. Compared to OPAMPs, which share similar structural features and application areas, VDBA circuits provide lower power consumption, higher bandwidth, and wider range linearity [20], [21]. The design of active filter circuits with VDBA can be very advantageous due to its superior features and the fact that the proposed circuits can be implemented without the use of external resistors. In the literature, active filter design and inductance simulations based on VDBA or voltage difference inverting buffer amplifier (VDIBA) are available [22]–[30].

The implementation of the biquad filter was carried out using a VDBA circuit block with CMOS technology parameters [24]. This study simulates the implementation of universal filters using FinFET-based VDBA with 32 nm PTM technology parameters. The new simulation results are compared to the implementation results of CMOS-based VDBA. The results of the FinFET-based operational transconductance amplifier (OTA) circuit, which is the basis of the VDBA structure, are compared with FinFET-based OTA design studies in the literature.

II. REALISATION OF VDBA-BASED FILTER CIRCUITS WITH FINFET

The schematic circuit symbol of the voltage differencing buffered amplifier (VDBA) is shown in Fig. 1, where high-impedance inverting and noninverting voltage inputs are denoted as V_P and V_N, high-impedance current output is denoted as I_Z, and low-impedance voltage output is denoted as V_W.

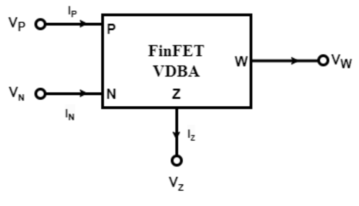

Fig. 1. The circuit symbol of the VDBA.

The VDBA circuit model can be described by the following set of equations

$$\begin{bmatrix} I_P \\ I_N \\ I_Z \\ V_W \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ g_m & -g_m & 0 \\ 0 & 0 & \alpha \end{bmatrix} \begin{bmatrix} V_P \\ V_N \\ V_Z \end{bmatrix}. \tag{1}$$

In the set of equations, g_m is the transconductance gain, representing the relationship between the output current and the input voltage. Transconductance gain measures the ratio of the change in input voltage to the change in output current. The VDBA can be adjusted electronically by changing the value of g_m, which is an important parameter in determining the amplifier characteristics. In the equation, α is the voltage ratio between the intermediate terminal output and the final output of the VDBA and is expressed as $\alpha = 1 - \varepsilon v$, where εv is the voltage tracking error. The magnitude of the tracking error, which measures the difference between the output voltage and the reference voltage, is much smaller than one. In the equation, $I_P = I_N = 0$ represents infinite input impedance for an ideal VDBA.

Figure 2 shows the complete circuit diagram for implementing a FinFET-based VDBA circuit that satisfies the equations. In the two-stage VDBA circuit, the first stage (X_1-X_8) is the operational transconductance amplifier (OTA), which converts the high-impedance voltage difference at the P and N terminals into the high-impedance output current at the Z terminal; the second stage (X_9-X_{15}) is the voltage buffer, which provides impedance matching by connecting to the current output of the OTA. Generally defined as a voltage-controlled current source, the OTA amplifies the current from the voltage difference at the input. There is an additional current input to control the transconductance gain of the amplifier, giving OTA electronic controllability.

The X_1 and X_2 N-type FinFETs form the basic differential amplifier structure. The output currents of the X_1 and X_2 FinFETs drive the diode-connected X_3 and X_4 FinFETs. Since the input resistance of the input transistors is ideally infinite and practically very high, the input currents are approximately zero. The Z terminal is the input terminal of the voltage buffer, and the W terminal is the output terminal of the voltage buffer, so the voltage values at the W and Z terminals are equal to each other. Current mirrors X_3-X_5 and X_7-X_8 transfer X_3-X_5 and X_7-X_8 transfer I_{DN} current, and current mirrors X_4-X_6 transfer I_{DP} current to terminal Z.

The voltage buffer placed between the first circuit with a high output impedance and the second circuit with a low input impedance prevents the second circuit from loading the first circuit. Because the input resistance of the voltage buffer circuit is high, ideally infinite, the output resistance is low, ideally zero. The main function of the voltage buffer is to copy the voltage by providing impedance matching.

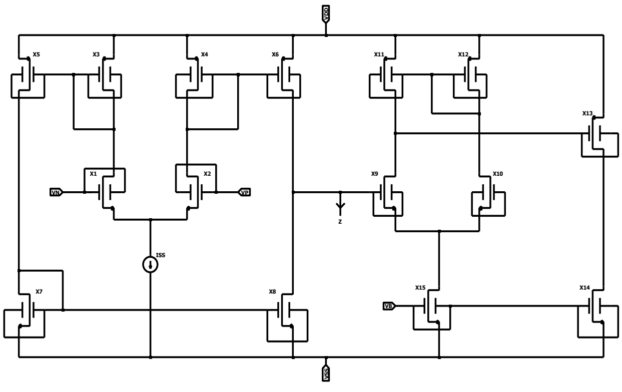

Fig. 2. FinFET implementation of the VDBA [14].

Figure 3 shows the circuit design of a three-input, single-output voltage-mode universal filter using a FinFET-based VDBA circuit. The node analyses of the circuit (Fig. 3) yield the following voltage transfer function

$$V_O = \frac{V_3 s^2\left(C_1C_2\alpha_2\right)+V_2 s\left(C_1\alpha_1\alpha_2\right)+V_1\left(g_{m1}g_{m2}\alpha_1\alpha_2\right)}{s_2\left(C_1C_2\right)+s\left(g_{m2}C_1\alpha_2\right)+\left(g_{m1}g_{m2}\alpha_1\right)}. \quad (2)$$

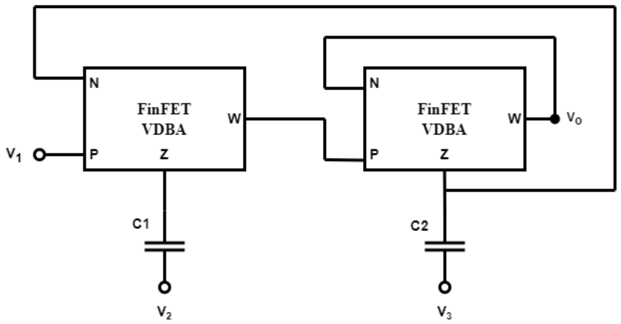

Fig. 3. FinFET VDBA universal filter configuration.

Table I shows five filter functions obtained from the transfer functions. These functions vary depending on the voltage state of the inputs V₁, V₂, and V₃ in the transfer function's numerator. Different combinations can be obtained with the low-pass filter, high-pass filter, band-pass filter, band-stop filter, and all-pass filter functions. As a result, a single circuit shown in Fig. 3 can realise all filter structures [31].

TABLE I. THE FILTER FUNCTIONS DEPENDING ON THE INPUT AND OUTPUT STATUS.

Filters	V_1	V_2	V_3	Output Functions (Vo)
LPF	V_{IN}	0	0	$\frac{V_1 g_{m1} g_{m2} \alpha_1 \alpha_2}{s^2 C_1 C_2 + s g_{m2} C_1 \alpha_2 + g_{m1} g_{m2} \alpha_1}$
HPF	0	0	V_{IN}	$\frac{V_3 s^2 C_1 C_2 \alpha_2}{s^2 C_1 C_2 + s g_{m2} C_1 \alpha_2 + g_{m1} g_{m2} \alpha_1}$
BPF	0	V_{IN}	0	$\frac{V_2 s g_{m2} C_1 \alpha_1 \alpha_2}{s^2 C_1 C_2 + s g_{m2} C_1 \alpha_2 + g_{m1} g_{m2} \alpha_1}$
BRF	V_{IN}	0	V_{IN}	$\frac{V_3 s^2 C_1 C_2 \alpha_2 + V_1 g_{m1} g_{m2} \alpha_1 \alpha_2}{s^2 C_1 C_2 + s g_{m2} C_1 \alpha_2 + g_{m1} g_{m2} \alpha_1}$
APF	V_{IN}	$-V_{IN}$	V_{IN}	$\frac{V_3 s^2 C_1 C_2 \alpha_2 - V_2 s g_{m2} C_1 \alpha_1 \alpha_2 + V_1 g_{m1} g_{m2} \alpha_1 \alpha_2}{s^2 C_1 C_2 + s g_{m2} C_1 \alpha_2 + g_{m1} g_{m2} \alpha_1}$

The pole frequency (w_o) and quality factor (Q) extracted from the transfer function of the universal biquad filter constructed with the FinFET-based VDBA circuit are defined as follows:

$$w_o = \sqrt{\frac{g_{m1}g_{m2}\alpha_1}{C_1C_2}}, \quad (3)$$

$$Q = \frac{1}{\alpha_2}\sqrt{\frac{g_{m1}C_2\alpha_1}{g_{m2}C_1}}. \quad (4)$$

Two essential parameters to examine whether the filter circuit results vary with component values are the resonant frequency (w_o) and the quality factor (Q). Sensitivity analyses concerning the active and passive elements that affect (w_o) and Q are calculated as in (5) and (6), and it is clear that the results do not exceed unity:

$$S_{g_{m1}}^{w_o} = S_{g_{m2}}^{w_o} = -S_{C_1}^{w_o} = -S_{C_2}^{w_o} = S_{\alpha_1}^{w_o} = \frac{1}{2}, S_{\alpha_2}^{w_o} = 0, \quad (5)$$

$$S_{g_{m1}}^{Q} = -S_{g_{m2}}^{Q} = -S_{C_1}^{Q} = S_{C_2}^{Q} = S_{\alpha_1}^{Q} = \frac{1}{2}, S_{\alpha_2}^{Q} = -1. \quad (6)$$

III. SIMULATION RESULTS

DC and AC analysis of the FinFET-based VDBA universal biquad filter circuit, using FinFET technology, was realised with the LTSpice programme using 32 nm FinFET technology parameters. Table II shows the aspect ratios of the transistors used in the simulation. The circuit realised has the supply voltage $V_{DD} = -V_{SS} = 0.2$ V, polarisation current $I_{SS} = 13$ µA, and the bias voltage $V_{B2} = -0.11$ V.

TABLE II. FinFETs ASPECT RATIOS FOR THE VDBA.

FinFETs	Width (W)	Length (L)
X_1, X_2, X_3, X_4, X_{10}, X_{11}, X_{15}, X_{16}	640 nm	32 nm
X_5, X_6	1920 nm	64 nm
X_7, X_8	640 nm	64 nm
X_{12}, X_{13}, X_{14}	1280 nm	32 nm

Figures 4 and 5 show the DC transfer characteristics of the input and output stages of the FinFET-based VDBA. The DC transfer characteristics of the input stage were obtained by plotting the I_Z current against the V_P voltage by grounding the N terminal from the input terminals, and the I_Z current against the V_N voltage by grounding the P terminal are plotted on the same axis in Fig. 4. The circuit parameters for both inputs are set so that the characteristics are symmetrical with respect to zero. Figure 5 shows the DC transfer characteristic (V_Z-V_W) of the output stage of the FinFET-based VDBA. The lower limit of the V_W voltage is -160 mV, while the upper limit is 125 mV. When the FinFET-based VDBA is supplied with ±200 mV, the output voltage swing is between -160 mV and 125 mV.

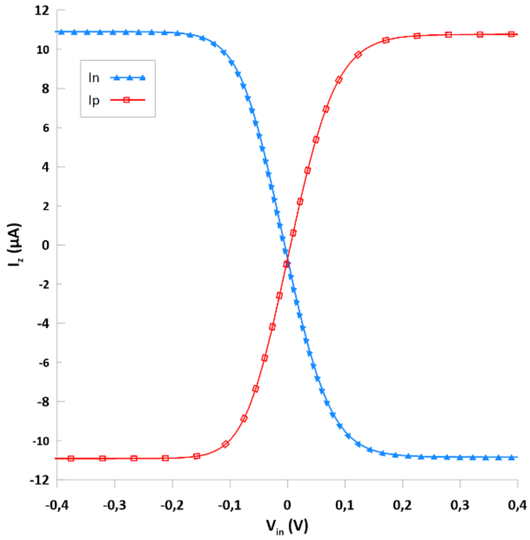

Fig. 4. The DC characteristic of the input stage of the FinFET-based VDBA.

Figures 6 and 7 show the AC transfer characteristics of the input and output stages of the FinFET-based VDBA. The AC transfer characteristics of the input stage were obtained by applying AC 1 V to the P terminal in the active circuit and grounding the N terminal. As in the I_Z/V_P simulation result shown in Fig. 6, the FinFET-based VDBA circuit has a transconductance gain of 136 µA/V and a bandwidth of 14.5 GHz. To extract the AC transfer characteristics of the output stage of the FinFET-based VDBA circuit, an AC voltage was applied to the Z terminal. Figure 7 shows the variation of the alpha value (V_W / V_Z) against frequency. The alpha value was measured to be approximately equal to 1, and the fixed bandwidth of the value is approximately 210 MHz.

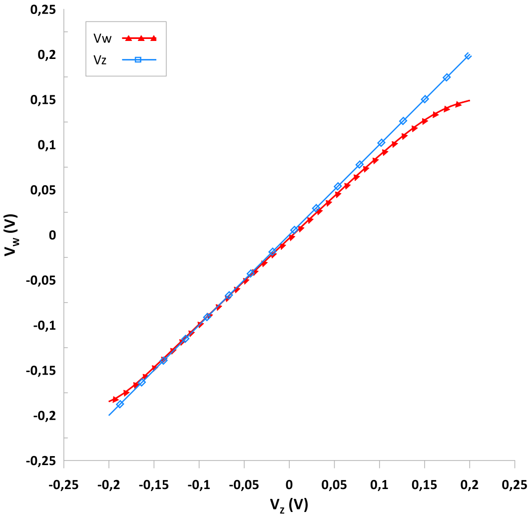

Fig. 5. The DC transfer characteristic of the output stage of the FinFET-based VDBA.

Figure 3 shows the simulation result of the universal filter configuration created with the FinFET-based VDBA designed with $C_1 = C_2 = 10$ pF for $gm_1 = gm_2 = 136$ µA/V. As a result of the corresponding simulations, the gain-frequency curves of the low-pass, high-pass, band-pass, and band-stop filters are shown in Fig. 8. Figure 9 shows the phase and frequency responses of the all-pass filter.

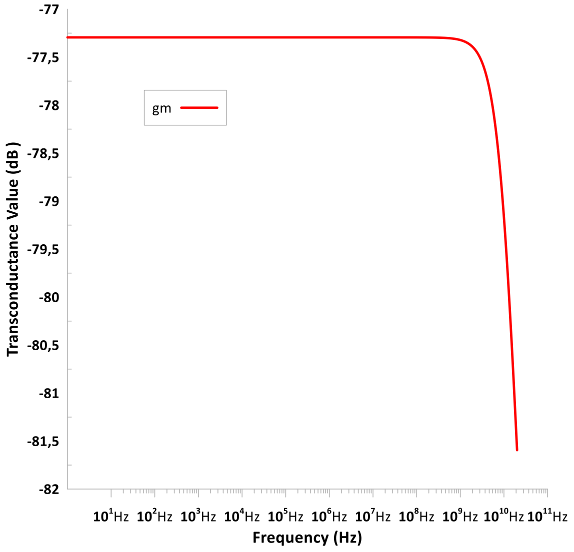

Fig. 6. The AC transfer characteristic of the input stage of the FinFET-based VDBA.

To test the FinFET VDBA based universal filter, a sinusoidal signal of 40 mV(p-p), 2.3 MHz is applied to the input of the band-pass filter, and the output waveform is obtained by LTspice simulations which are shown in Fig. 10. The dependence of the output harmonic distortion of band-pass filter on input voltage amplitude is illustrated in Fig. 11. The total harmonic distortion (THD) result shows that for an input signal up to 100 mV(p-p), the THD remains in acceptable limits.

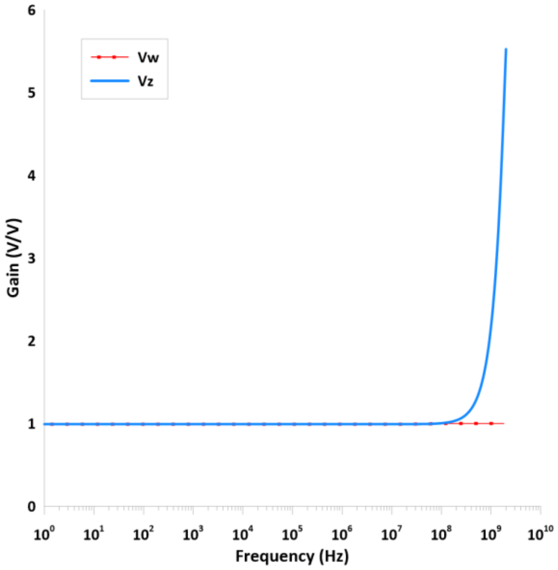

Fig. 7. AC transfer characteristic of the output stage of the FinFET-based VDBA.

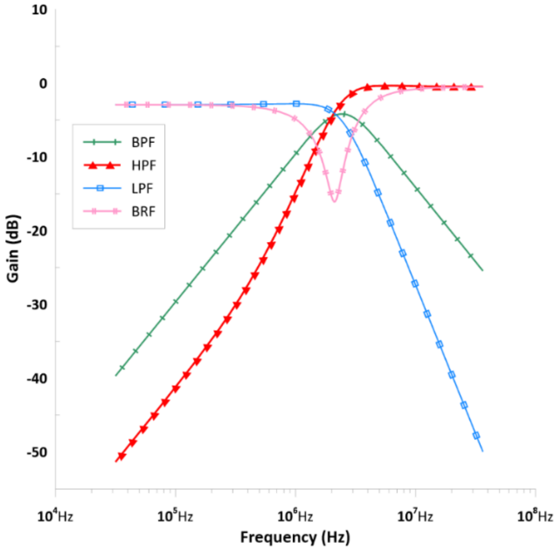

Fig. 8. Simulated results of the gain frequency responses of the universal filter.

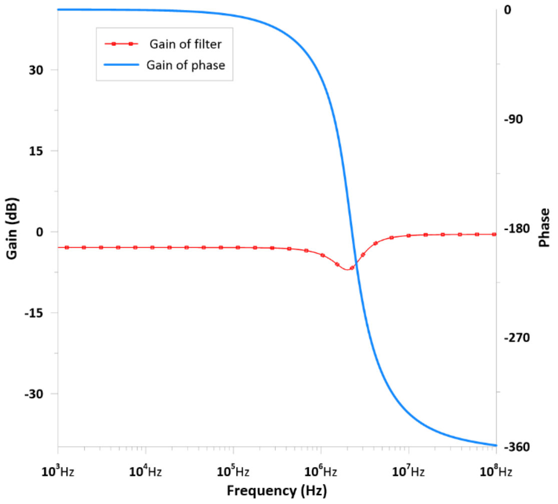

Fig. 9. Gain and phase frequency responses of the all-pass filter in the universal filter.

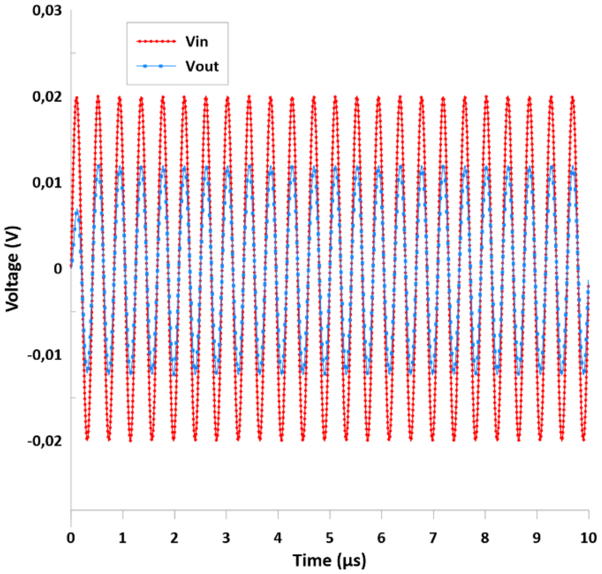

Fig. 10. The input and output waveforms of the FinFET VDBA-based band-pass filter at 20 mV, 2.3 MHz, AC input signal.

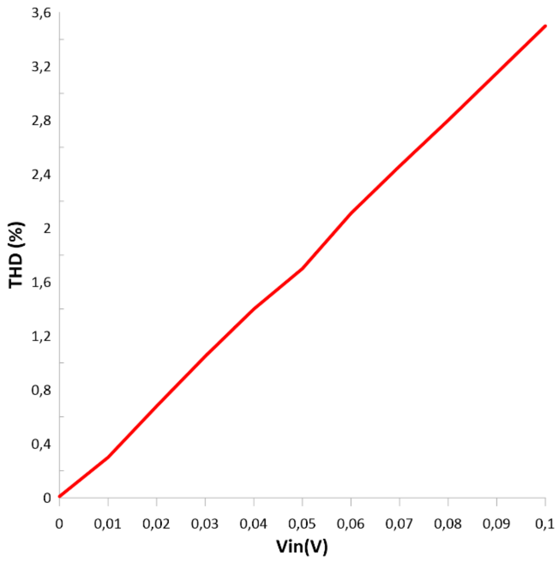

Fig. 11. Dependence of output voltage harmonic distortion on input voltage amplitude of FinFET VDBA-based band-pass filter.

The simulation results that compare the circuit performance of FinFET-based VDBA circuits and CMOS-based VDBA circuits and filter applications are shown in Table III.

The FinFET-based VDBA circuit is based on OTA. Therefore, the performance of OTA circuits realised with FinFET in the literature and the simulation results of our implementation are compared in Table IV. Analysing the results, it is clear that the performance of the circuit realised within the scope of the study is better than the results in the literature in terms of supply voltage, power consumption, transconductance, and especially bandwidth.

In the FinFET-based VDBA circuit realised, the input impedance value is 315 GΩ, the output impedance measured at the Z terminal is 29 kΩ, and the output impedance measured at the W terminal is 51 kΩ. According to the simulation results, the FinFET-based VDBA circuit outperforms CMOS-based circuits in terms of dimensions, supply voltage, power consumption, bandwidth, and filter cut-off frequency and bandwidth. Therefore, FinFET is a promising alternative technology to MOSFET for nanoscale design.

TABLE III. COMPARISON OF PERFORMANCE PARAMETERS OF VDBA

Parameters	**[24]**	**[23]**	**[27]**	**FinFET VDBA**
Technology	0.18 μm TSMC	0.18 μm TSMC	0.18 μm TSMC	32 nm PTM
Supply Voltage	±1.5 V	±2 V	±0.2 V	±0.2 V
Power Consumption	0.97 mW	1.4 mW	6.22 nW	10.8 μW
Linearity Range	±140 μA	NA	≈ ±3 nA	±10.8 μA
Input Voltage Range	≈ -1.5 V– +1.12 V	≈ ±0.8 V	-145 mV– +200 mV	-160 mV– +125 mV
Transconductance	748 μA/V	79 μA/V	64 nA/V	136 μA/V
Bandwidth	100 MHz	≈ 69 MHz	≈ 1 kHz	745 MHz
LPF Cut-off Frequency	≈ 8 MHz	≈ 60 kHz	≈ 150 Hz	3 MHz
HPF Cut-off Frequency	≈ 1.5 MHz	≈ 40 kHz	≈ 90 Hz	2.3 MHz
BPF Center Frequency	≈ 1.5 MHz	≈ 46.9 kHz	≈ 100 Hz	2.3 MHz
BPF Bandwidth	≈ 7.5 MHz	≈ 40 kHz	≈ 40 Hz	3 MHz
BRF Center Frequency	≈ 1.5 MHz	NA	≈ 100 Hz	2.3 MHz
BRF Bandwidth	≈ 500 kHz	NA	≈ 20 Hz	600 kHz
BRF Reject Ratio	≈ 85 dB	NA	≈ 28 dB	20 dB

TABLE IV. PERFORMANCE PARAMETER COMPARISON FinFET-BASED OTA.

Parameters	**[32]**	**[33]**	**[34]**	**FinFET OTA**
Technology	45 nm PTM	32 nm PTM	32 nm PTM	32 nm PTM
Supply Voltage	±0.5 V	±1.5 V	±0.85 V	±0.2 V
Power Consumption	NA	NA	25.42 μW	10 μW
Linearity Range	NA	NA	NA	±10.8 μA
Gain	19.1 dB	13 dB	47.43 dB	12 dB
Transconductance	20.96 μA/V	NA	NA	136 μA/V
Transconductance (dB)	-93.57 dB	NA	NA	-77 dB
Bandwidth	≈ 35 MHz	161.3 MHz	174 MHz	14.5 GHz

Note: NA - Not Available.

IV. CONCLUSIONS

This study presents the FinFET-based realisation of voltage differencing buffered amplifier (VDBA) and implementation of three-input and single-output universal filter with FinFET-based VDBA without using passive elements. FinFET-based VDBA consumes only 10.8 μW of power, which is a deficient value for power consumption compared to previous studies. In addition, the bandwidth of the input stage of the circuit is measured to be 14.5 GHz, and the bandwidth of the VDBA circuit is measured to be 745 MHz, which is quite high for filter applications and high-frequency circuits. The VDBA circuit, which uses FinFET technology, was tested with a filter application and can successfully perform all filter configurations. The study results were compared with VDBA circuit and filter applications designed using conventional CMOS technology. According to Table III, the VDBA application implemented using conventional CMOS technology has a supply voltage of ±1.5 V. However, this has been reduced to ±0.2 V with FinFET technology, decreasing power consumption from

0.97 mW to 10.8 μW. In another paper [27], although the supply voltage is 0.2 V and the power consumption is 6.22 nW, the frequency range in which the circuit will operate is quite low.

Furthermore, the transistor size was reduced from 0.18 µm to 32 nm. In addition to significant advantages in dimension, supply voltage, and power consumption, the bandwidth has been increased from 100 MHz to 745 MHz. The significant increase in bandwidth shows that the circuit can be easily preferred in high-frequency applications. At the same time, according to the comparison of the results of the FinFET-based OTA circuit realised in this study with the FinFET-based OTA circuit in the literature, the supply voltage, power consumption, transconductance, and bandwidth values in our study are much better than those in the literature. For example, in the OTA circuit, which is the input stage of the VDBA circuit, the bandwidth is increased from 174 MHz to 14.5 GHz compared to other OTA studies with FinFET. According to the simulations, FinFET-based VDBA and its filter implementations gave successful results. The successful results show that FinFET technology is superior to CMOS technology in analogue circuit design with advantages such as lower supply voltage, lower power consumption, higher bandwidth, and smaller dimensions. As a result of all this information and findings, it is understood that the study is very efficient. The realised FinFET-based VDBA circuit and filter will be useful in the design of signal processing and biomedical applications. This study is expected to be a reference and useful for future research on this topic.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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