An Operational Transconductance Amplifiers Based Sinusoidal Oscillator Using CNTFETs

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***Abstract*—A new sinusoidal oscillator using Carbon Nanotube Field Effect Transistors (CNTFET) based Operational Transconductance Amplifiers (CNOTA) with grounded capacitors is presented in this paper. The proposed current-mode oscillator thus implemented and having grounded capacitor feature, fulfils the need for realizations of systems used in combination with various other systems/ subsystems - both voltage-mode and current mode. It also ensures simplicity in implementation by using a single-ended CNOTA. The analytical model is given for the circuit leading to fulfilment of the condition of oscillation at tuned frequency. The proposed sinusoidal oscillator is primarily used in the field of signal dispensation applications, telecommunication networks, communication-equipment and control modules. The benefits derived from the introduced model are validated by simulation carried out at a supply voltage of ±1.8 V in Cadence virtuoso using spectre model libraries. They are further tested with the aid of 32 nm model of Carbon Nanotube Field Effect Transistor (CNTFET) technology obtained through open source. The proposed design (and the model provided) is found to be in good agreement with the obtained results.**

***Index Terms*—Carbon Nano Tube Field Effect Transistor (CNTFET), Frequency of Oscillations, Grounded Capacitors, Operational Transconductance Amplifiers (OTAs), Condition of Oscillations, Sinusoidal Oscillator.**

I. INTRODUCTION

The demand for low powered and highly miniaturized systems is still mostly met through the best of Complementary Metal Oxide Semiconductor (CMOS) designs. It is the biggest leading improvised technique followed for the last few decades in the industry. However with the reduction of design parameters of MOS transistors to ensure scaling down of the device into deep nanoscale metrics as per requirements of circuit-designers, the CMOS technology is faced with numerous hurdles and complexities. These include increased current leakage, more power density, parametric differences and loss of control over gate. This definitely questions the use of CMOS technology to implement reduced power, performance elevated compact circuits [1-3]. These challenges could be overcome by introducing the recently developed CMOS nano-devices viz CNTFET, Quantum Dot Cellular Automation (QCA) and also Single Electron Technology (SET), which are believed to be able to replace conventional CMOS technology [4] in the near future. More advantages could be ensured with lesser power dissipation and highly compact designs at low supply voltage for easy ballistic transport. It attributes to making abstinence of high-speed operation that elevates utility of the devices to make it more apt for ultra large-scale integration to achieve low power yet high performance.

On scrutiny of the already mentioned nano-devices MOSFET and CNTFET are found to have more similarity in electrical characteristics allowing the latter to replace the former in circuits and systems for enhanced performances. The CNTFET technology has also been rated to be the most relevant among nanotechnologies. Compared to MOS transistors, CNTFET offers very less power dissipation and achieves greater carrier velocity at maximum level and elevated transconductance [5], [6].

Many varieties of sinusoidal oscillators play important roles in discharging their functions in communication equipment, control modules, signal dispensation appliances, measurement blocks etc. The whole concept of oscillator design depends on need based sinusoidal signal. The realization of a sinusoidal oscillator using voltage and current mode approaches adopted recently has contrasting character. While voltage mode uses operational amplifier based designs, the later are designed with OTAs, transconductance-C or gm-C techniques having electronic tunability in addition guaranteed high frequency performance. Among these, the design engineers prefer gm-C based sinusoidal oscillators using CMOS as well as CNTFET as they are more suitable for integrated circuit fabrication. However, the CMOS technology is going to be immoderate due to the limitations like extreme short channel effects, leakage current, source to drain tunneling, high leakage current process variations and lithographic limitations [7]. So, in order to overcome these disadvantages of CMOS (MOSFETs), CNTFETs are

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preferred.

The operational transconductance amplifiers and capacitors are components of choice to implement oscillators. Circuits composed of OTA-C's are graded as highly desired [8] for both linear and nonlinear monolithic analogue operators at high frequency, continuous time synthesis.

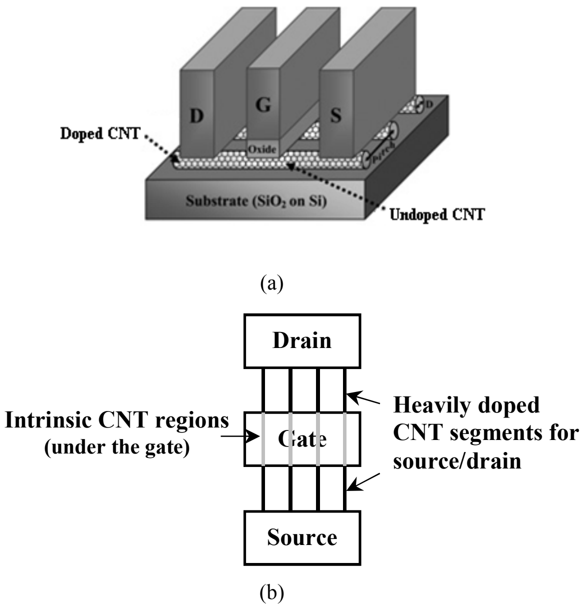
Simultaneously high-level research has been carried out over the improvement of productivity, particularly with regards to parts and devices in the electronics industry. Various electronic components are taken into consideration for generating number of circuits for analogue signal processing applications ranging from vacuum devices to designer friendly semiconductors in the different modes of discrete and the integrated (IC) versions [9].

The voltage mode methodology proposed for the circuits in the literature uplifted the typical parameters like performance and accuracy that has produced high frequency outputs designed with simplified topologies. This is found to be an economically reliable model. The requirements for suppressing supply-voltage however has increased in the recent past because of usage of these blocks in wireless applications where compact batteries are provided to drive it. This gave way to the current mode methodology where too similar benefits have been seen or harvested. It offers a number of advantages in terms of increased slew rate, extended dynamic range, high linearity, larger bandwidths and simplicity in realization [10]. Various oscillator circuits are provided in the literature with OTA as the leading block having grounded capacitor feature. It is found to be suitable for monolithic IC technology and thin film fabrication as it is less sensitive to parasitics and noise [11], [12]. Of these A. Srinivasulu et al in [13] presented a nearly similar topology as proposed by these authors here although their transfer function had a lower-valued constant term resulting in lower centre-frequency. However the real motivation was the concurrent interest to harvest the benefits of CNTFET that these authors have exploited in the proposed design. Hence before presenting the proposed design, an overview of CNTFET is presumed to be appropriate and follows next.

1.1. The Behavioural Model of The CNTFETs

The physical appearance of nanotube is of graphite with a rolled sheet of structure. The investigation of soot between the graphite electrodes in an arc discharge experiment conducted by Lijima in 1991 led to the invention of concentrically nested carbon structures who named it as multi walled carbon nano-tubes (MWCNTs). Later on Lijima and Ichihashi [14] of NEC Corp., with Bethwneetal of the IBM Research Centre, San Jose discovered other structure of carbon nanotube and named it as single walled carbon nanotube (SWCNTs). Carbon nanotubes are of two types based on its structure as SWCNT and MWCNT, SWCNT possess single cylinder and MWCNT contains more than one cylinder [15]. The properties of nanotube are highlighted in accordance with its chirality vicar and it can be elaborated as (n, m). The nature of carbon tube is such that either it acts as a conductor or as a semiconductor in accordance with that of (n, m) angles.

Carbon-tube of SWCNT structure acts as a conductor when n - m = 3t, where 't' represents a numeral, else it behaves like a conductor [16]. Mostly, the conducting paths in CNTFET's are semi conducting SWCNT's only. The primary difference between the CNTFETs and MOSFETs is in its carrier mobility and driving current strengths, which are the same only for CNTFETs of both P and N models but not for MOSFETs. The flexibility is afforded to CNTFETs of more compact designs where the scaling and sizing adjustments are carried out easily in highly complex circuits [17]. The more analogous behaviour in I-V characteristics of the CNTFET in contrast to MOSFET is a crucial enhancement in CNTFET. The schematic and cross sectional view of the CNTFET is shown in Fig 1(a) and Fig 1(b) respectively [18], [19]. The number of pins in both CNTFET and MOSFET are four and the same can be observed from the figures provided. Assumptions similar to MOSFETs are made for CNTFET in order to satisfy the behavioral aspects not being available from the traditional silicon components.



(a)

(b)

Fig. 1. Schematic diagram of CNFET device (a) Cross sectional view; (b) Top view.

In the interest of researchers, carbon nanotubes (CNT) and CNTFET are the favoured material already replacing silicon [20]. The specific properties offered by this material are more thermal conductivity than diamond, greater electrical conductivity than silver apart from having high tensile behaviour than steel [21]. The main advantage in using CNT is that its capacity is almost equal to 1D ballistic transport. It is found at below the low voltage bias due to ultra long (~1 μm) scattering of mean free paths (MFP). This 1D structure ensures improved electrostatic control over the channel compared to the 2D and 3D structures. CNTFET is similar to MOSFET channel replaced with parallel arrangement of CNTs. This causes non-mobility charge carriers due to the 1D ballistic transport. It is established as an emerging and reliable device in view its aforesaid properties substituting conventional silicon technology [17, 22].

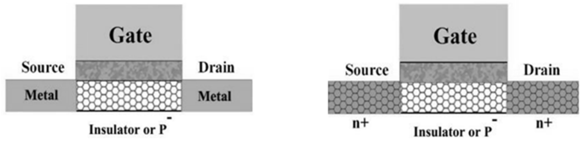
To reap the benefits of CNTFET, an oscillator application based on N and P type CNTFETs has been realized. On the whole, these four terminal components consisting of nanotubes of semiconducting nature behave as a link connecting a source and drain terminal of the device. In contrast to that of chirality vector, based on the operation of the device the CNTFETs are categorized into Schottky barrier CNTFET (SB-CNT) and MOSFET like FET (MOS-CNT). They are presented with details in Fig 2 (a) and Fig 2(b) respectively [23], [24]. The SB-CNTFETs' device conductivity is tuned using the tunneling of the majority charge carriers on terminal contacts through a Schottky barrier on current which is accomplished with the resistance over contacts. The adjustment of Fermi level in metal and semiconductor is achieved by deploying Schottky barriers at source and drain contacts. The conductivity is regulated using electrostatic effect at the gate terminal of Schottky barriers. The same technique is applied through height and width adjustments, whereas, the ambipolar behaviour is observed in the SB-CNTFET. Further, unipolar nature is exhibited in MOSFET as in CNTFET and both are from electron (PCNTFET) or hole (NNTFET) transport.

The CNTFET's mathematical relation for threshold voltage is determined by (1)

$$V_{th} \simeq E_{bg}/2e \simeq 0.436/D_{cnt} \text{ (nm)} \quad (1)$$

where E_{bg} is the energy band gap of carbon nano-tube, e is the charge of electron and D_{cnt} is the diameter of the carbon nano-tube. It can be seen from (1) that the threshold voltage of a CNTFET is inversely related to the diameter of its nano-tubes, which is computed by (2)

$$D_{CNT} = d = 0.0783\sqrt{(m^2 + n^2 + mn)} \quad (2)$$



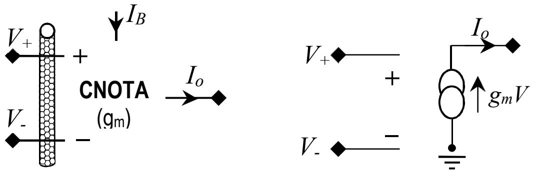
(a) (b)

Fig. 2. (a) SB-CNFET; (b) MOS-CNFET

1.2. Basic Concept of OTA

The symbolic representation of CNOTA and its equivalent circuit model are depicted in Fig 3 (a) and (b) respectively. However, CNTFET implementation is shown in Fig 4 [25]. Ideally, the OTA consists of infinite impedance across both input and output nodes. The OTA expression for output current is represented by

$$I_O = g_m(V_+ - V_-) \quad (3)$$



(a) (b)

Fig. 3. (a) CNTFETs OTA Symbol (CNOTA); (b) Equivalent circuit

From (3), it can be observed that the notation of transconductance represented by g_m is altered with the help of externally applied bias current (I_B). The mathematical expression is given by

$$g_m = I_B/2V_T \quad (4)$$

where thermal voltage is represented by V_T in (4). CNOTA has three terminals of which two are for inputs – one for inverting (V-) and the other for non-inverting (V+); while the third terminal I_{OUT} acts as an output. Apart from these, it has another input for biasing, represented by I_B. The differential potential appears across the input terminals resulting in the current at the output node proportional to the input-differences. It makes CNOTA a voltage controlled current source (VCCS). This feature enables the transconductance of the amplifier regulated by the bias current as an input. CNOTA offers a high impedance feature for its differential input stages. It also provides scope for usage of negative feedback, which is similar to that of the conventional voltage operational amplifier.

The bias current I_B is used to control CNOTA transconductance to the anticipated level. Grounded capacitor based CNOTAs can have high frequency performance and yet, chip area optimization. In this paper a new sinusoidal oscillator in current mode has been proposed and presented with electronic tunability by three single-ended CNOTAs and two-coupling capacitors. The grounded capacitors have resulted in the simplicity and suitability of the topology involved. As compared to multiple outputs CNOTA this single ended CNOTA technology is advantageous in IC fabrication. The proposed design has derived it.

II. PROPOSED SINUSOIDAL OSCILLATOR TOPOLOGY WITH CARBON NANOTUBE BASED OTAS DESCRIPTION AND ANALYSIS

The proposed circuit of sinusoidal oscillator is presented in Fig 2. It has two grounded capacitors and CNOTA as the main components. The transconductance of the proposed circuit CNOTAs are varied concurrently with the help of additional bias current I_B which is not shown in the figure. The frequency tuning is carried out either by simultaneously varying the (same) bias current or by varying the grounded capacitors externally connected to the CNOTAs. Varying the frequency of oscillation independently without affecting condition of oscillation are the main advantages which is illustrated analytically next.

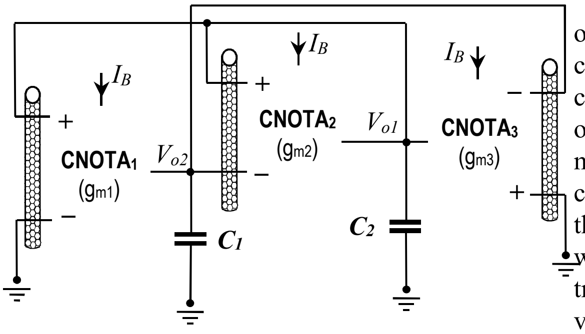


Fig. 4. Proposed sinusoidal oscillator circuit using three COTAs with two grounded capacitors

The ideal behaviour of the proposed oscillator circuit and its characteristic equation is expressed in the form of a second order equation as given below:

$$s^2 - bs + \omega_0^2 = 0 \qquad (5)$$

In the above equation the terms b and $\omega_o{}^2$ represent the combination of the transconductance-gain and the values of capacitor used with the CNOTA. The condition of oscillation for the transconductance-amplifier-capacitor-oscillator (TACO) can be altered by b. The frequency of oscillations is given by $\omega_o{}^2$. Further, it can be concluded that the change taking place in $\omega_o{}^2$ is due to the tranconductance gain that automatically brings out a proportional change in the quantity b [1].

By considering the behavioural model of the proposed circuit and ideal characteristics of the OTA as shown in Fig 3, the mathematical notation of characteristic equation is derived as:

$$s^2 - s[g_{m3}(C_1+C_2)/C_1C_2] + [g_{m3}(g_{m1}+g_{m2}) + g_{m1}g_{m2}]/C_1C_2 = 0 \qquad (6)$$

If the transconductances of the OTA's are varied simultaneously through a single external current, then the condition of oscillation (CO) is obtained by fulfillment of both the following equations:

$$g_{m1} = g_{m2} = g_{m3}, for\ I_{B1} = I_{B2} = I_{B3} \qquad (7)$$

and $$\omega^2 = [g_{m3}(g_{m1} + g_{m2}) + g_{m1}g_{m2}]/C_1C_2 \qquad (8)$$

The frequency of oscillation (FO) for the proposed design configuration is once again derived from (6) which is reduced from (8):

$$\omega = (g_m / \sqrt{C_1C_2}) \qquad (9)$$

For sustaining the oscillation the relation between the two capacitors must be: C2 ≥ C1. The relationship between the transconductance g_m and external bias current I_B can be defined using mathematical model as

$$g_m = I_B / 2V_T \qquad (10)$$

Combining (7) and (9) the frequency of oscillations (FO) is written as:

$$f = \frac{g_m}{2\pi\sqrt{C_1C_2}} \text{ (or) } f = \frac{I_B}{4\pi V_T\sqrt{C_1C_2}} \qquad (11)$$

From (11) above it is confirmed that the frequency of oscillation is tuned linearly by using external current as shown in Fig 4. The value of the grounded capacitors C1 or C2 produces the required condition of oscillations. This approach of grounded capacitor is more relevant in the case of IC implementation as well controlling the frequency of oscillations. Thus we see that while the CO can be independent controlled, FO will depend on the current value and thus the transconductances as well. For our simulation we varied the IB from 40 μA to 140 μA for reasonable linearity.

III. SPECTRE SIMULATION AND EXPERIMENTAL RESULTS

3.1 Simulation Results:

Fig. 5 represents the CNTFET OTA (CNOTA) use by these authors. This is derived from the version presented in [25]. The complete design of Fig 5 needs three CNOTAs presented in Fig 4 apart from the two grounded capacitor elements. The circuit provided in Fig 4 was simulated with the CNTFET 32 nm technology Spectre model parameters with a supply voltage of ±1.8 V. The sine wave is produced with C_1 = 1 nF, C_2 = 5 nF and IB = 50 μA, which yields the waveform with time period T=4.2 ns. The calculated value from the equation (11) is 4.0 ns and the same is presented in Fig. 6. The small error (≈ 5%) is attributed to model parameter-non-idealities.

The simulated results of transient response, noise analysis and noise sensitivity of the design of Fig. 4 using Monte Carlo simulation at minimal corners is next carried out and the plots are included in Fig. 8 and 9. Once again the results are very encouraging.

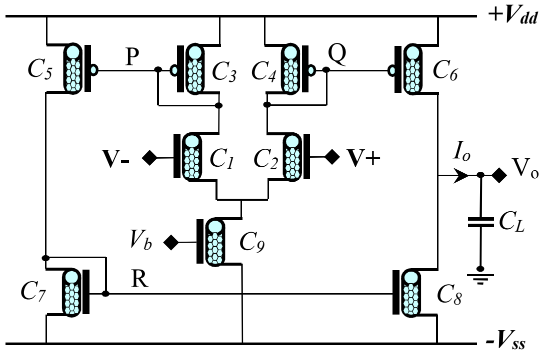


Fig. 5. CNTFET implementation of OTA [47]

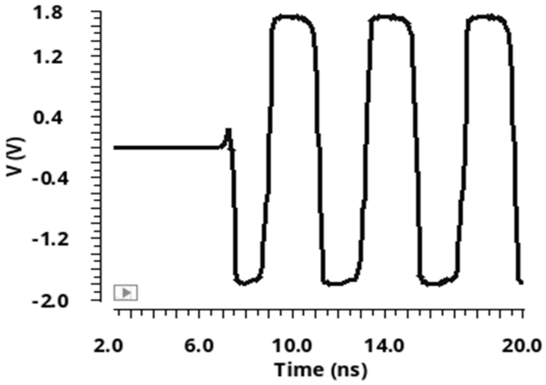


Fig. 6. Output waveform of CNOTA oscillator of Fig. 4

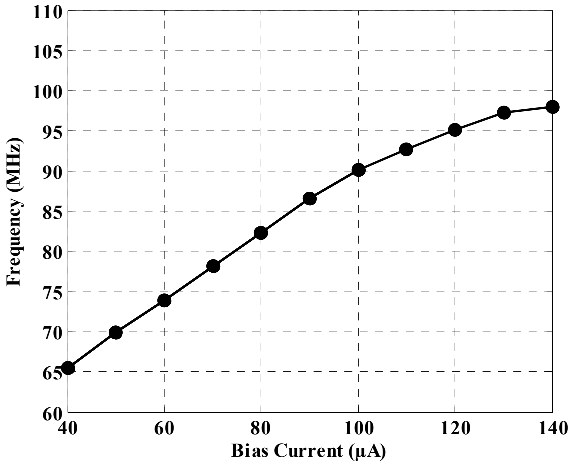


Fig. 7. Oscillation frequencies versus bias currents

Fig. 7 gives the linear-range of frequency tuning and relevant results of simulation are presented for the proposed sinusoidal oscillator. The bias current is tuned and the corresponding values of the frequency of oscillations are plotted. The design parameters for this, once again, are $C_1 = 1\ nF$ and $C_2 = 5\ nF$ and the supply voltage is ± 1.8 V. These values are adopted throughout the design for tunability requirement and validation with other designs as well as for benchmarking. The analyses from the theoretical model of the design are once again in close agreement with the simulated results. The temperature stability of the introduced circuit is next tested from 0°C to +150°C and observed deviation of temperature variance of the sinusoidal signal is ≈ 0.012%, which is a very encouraging performance justifying the use of CNTFET.

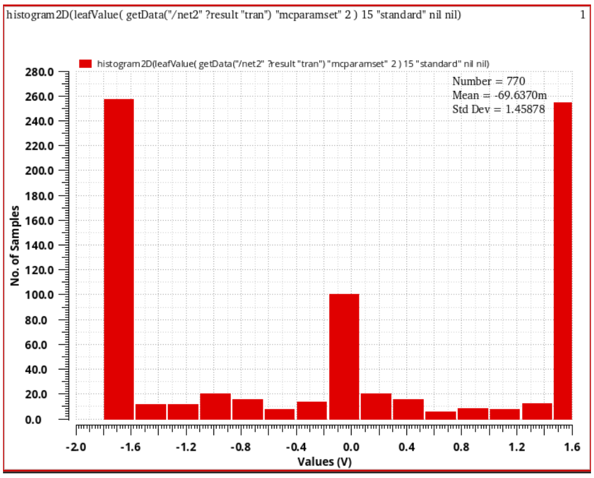


Fig. 8. Monte Carlo analysis of Transient Response

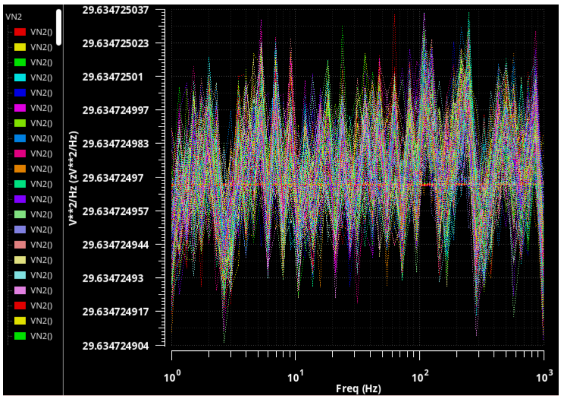


Fig. 9. Monte Carlo analysis of noise analysis and sensitivity.

IV. SENSITIVITY

The Classical sensitivity (S_x^y) for parameter y with respect to parameter x has been defined as,

$$S_x^y = \frac{\dfrac{\delta y}{y}}{\dfrac{\delta x}{x}} = \frac{x}{y}\cdot\frac{\delta y}{\delta x} \qquad (12)$$

Applying this for (9) it is easy to find $S_{g_m}^T$, $S_{C_1}^T$, and $S_{C_2}^T$ which are given by,

$$S_{g_m}^T = -1 \qquad (13)$$

$$S_{C_1}^T = S_{C_2}^T = 0.5 \qquad (14)$$

Obviously, in the summation to find the net sensitivity ($S = \sum_{x=g_m,C_1,C_2} S_x^T$), it can be easily verified that the sensitivities for g_m, C_1, and C_2 completely cancel out. As such the proposed configuration can be confirmed to be stable against component sensitivity as per the classical definition [26-30].

V. CONCLUSIONS

One novel oscillator circuit built by using three CNOTAs with grounded capacitors for sinusoidal waveform generation is proposed in this paper. The design uses CNTFET technology models with 32 nm Spectre libraries taking supply voltage to be ±1.8 V. By varying either the capacitors C_1, C_2 or bias current I_B, the oscillator frequency can be tuned or adjusted. Tunability of grounded capacitors is an attractive feature of the design as it provides an easy option for digital control by programmable switched capacitor array (PSCA) as compared to tuning by bias-current, as explained in [30]. The component's sensitivity is very good; making it there by a candidate design for integration. A number of applications are highlighted for the proposed configuration from electronic and communication domains with special emphasis on power conversion applications, telecommunication networks and sensor modules applications. The excellent temperature sensitivity, linearity and minimization of leakage justify the use of more expensive CNTFET technology to promise a superior design of choice for the future.

REFERENCES

[1] M. Hossein, M. Faghih, K. O. Akbar, A universal method for designing low-power carbon nanotube FET-based multiple-valued logic circuits, IET Comput. Digit. Tech. 7 (2013) 167-181.

[2] K. Patcha, S. Musala, K. Vijayavardhan, Y. S. Vani, A. Srinivasulu, Carbon Nano Tube Field Effect Transistors Based Ternary Ex-OR and Ex-NOR Gates, Current Nanoscience, 12 (2016) 520-526.

[3] S. Zahiruddin, A. Srinivasulu, A high frequency tunable sinusoidal oscillator using single CCCII+, In: proc. of the 2015 International Conference on Control, Instrumentation, Communication and Computational Technologies (ICCICCT), 2015, pp. 462-465.

[4] A. T. Mohammad, S. Farshad, H. M. Mohammad, N. Keivan, Design and implementation of multi-stage interconnection networks using quantum-dot cellular automata, Microelectronics Journal, 42 (2011) 913-922.

[5] A. E. Seyyed, R. R. Mohammad, B. Ali, S. Mahyar, Efficient CNTFET-based design of quaternary logic gates and arithmetic circuits, Microelectronics Journal, 53 (2016) 156-166.

[6] M. H. Moaiyeri, N. Khastoo, M. Nasiri, K. Navi, N. Bagherzadeh, An Efficient Analog-to-Digital Converter Based on Carbon Nanotube FETs, Journal of Low Power Electronics, 12 (2016) 150-157.

[7] A. U. Fahad, H. Mohammad, Carbon nanotube field effect transistors for high performance analog applications: An optimum design approach, Microelectronics Journal, 41 (2010) 395-402.

[8] M. Gupta, New Single Input Multiple Output Type Current Mode Biquad Filter Using OTAs, Circuits and Systems, 7 (2016) 231-238.

[9] S. Saksit, T. Chanchai, J. Winai, OTA Based Current-mode Sinusoidal Quadrature Oscillator with Non-interactive Control, Przeglad Elektrotechniczny, 88 (2012) 14-18.

[10] S. J. Gift, B. Maundy, An improved multiphase sinusoidal oscillator using current feedback amplifiers, International Journal of Electronics Letters, 4 (2016) 177-187.

[11] M. Hasan, Z. Yanqing, S. Yichuang, Design for testability of high-order OTA-C filters, International Journal of Circuit Theory and Applications, 44 (2016) 1859-1873.

[12] M. T. Abuelma'atti, Recent Developments in Current-Mode Sinusoidal Oscillators: Circuits and Active Elements, Arabian Journal for Science and Engineering, (2016) 1-32.

[13] A. Srinivasulu, G. Sowjanya, Gautham S. H, T. Pitchaiah and V.V.S.V. Krishna, "Operational Transconductance Amplifiers based sinusoidal oscillator with grounded capacitors", Lecture Notes in Electrical Engineering, Chapter No: 28, vol. 403, pp. 343-352.

[14] T. Cui, L. Lin, L. C. Qin, W. Sean, Direct measurement of chiral structure and transport in single-and multi-walled carbon nanotubes, Journal of Physics: Condensed Matter, 28 (2016) 475302(1-6).

[15] G. Chen, S. Sakurai, M. Yumura, K. Hata, D. N. Futaba, Highly pure, millimeter-tall, sub-2-nanometer diameter single-walled carbon nanotube forests, Carbon, 107 (2016) 433-439.

[16] S. Lin, Y. B. Kim, F. Lombardi, Design of a ternary memory cell using CNTFETs, IEEE Transactions on Nanotechnology, 11 (2012) 1019-1025.

[17] F. Sharifi, H. M. Mohammad, N. Keivan, B. Nader, Ultra-low-power carbon nanotube FET-based quaternary logic gates. International Journal of Electronics, 103 (2016) 1524-1537.

[18] J. Deng, 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 Trans. Electron Devices, 54 (2007) 3186-3194.

[19] J. Deng, H. S. P. Wong, A compact SPICE model for carbon-nanotube field-effect transistors including nonidealities and its application–part ii: full device model and circuit performance benchmarking, IEEE Trans. Electron Devices, 54 (2007) 3195-3205.

[20] Y. B. Kim, Integrated circuit design based on carbon nanotube field effect transistor, Transactions on Electrical and Electronic Materials, 12 (2011) 175-188.

[21] A. L. Sajad, M. Nizamuddin, S. Humyra, B. Faisal, M. M. Asim, R. A. Abdul, A. A. Shuja, Carbon Nanotube Based Operational Transconductance Amplifier: A Simulation Study, Transactions on Engineering Technologies (Springer Netherlands), 2014; pp. 231-242.

[22] J. Appenzeller, Carbon nanotubes for high performance electronics, Proceedings of the IEEE, 96 (2008) 201-211.

[23] K. Melzer, V. D. Bhatt, E. Jaworska, R. Mittermeier, K. Maksymiuk, A. Michalska, P. Lugli, Enzyme assays using sensor arrays based on ion-selective carbon nanotube field-effect transistors, Biosensors and Bioelectronics, 84 (2016) 7-14.

[24] M. L. Geier, M. Karttikay, B. Stephen, R. M. Seth, C. H. Mark, Controlled n-type doping of carbon nanotube transistors by an organorhodium dimer, Nano letters, 16 (2016) 4329-4334.

[25] S. A. Loan, M. Nizamuddin, A. R. Alamoud, S. A. Abbasi, Design and comparative analysis of high performance Carbon Nanotube-based Operational Transconductance Amplifiers, NANO, 10 (2015) 1-11.

[26] A. S. Sedra, K. C. Smith, Microelectronic Circuits, 4th ed.; Oxford University Press, 1998.

[27] V. Vijay, A. Srinivasulu, A DCCII based square wave generator with grounded capacitor, In: proc. of the 2016 International Conference on Circuit, Power and Computing Technologies (ICCPCT), 2016, pp. 1-4.

[28] A. Srinivasulu, V. Tejaswini, T. Pitchaiah, Time Marker Generator Using Operational Transconductance Amplifier, Jurnal Teknologi, 76 (2015) 103-105.

[29] M. Suma, V. V. Reddy, A. Srinivasulu, Current mode Schmitt trigger based on ZC-Current Differencing Transconductance Amplifier, In: proc. of the IEEE International Conference on Inventive Computation Technologies (ICICT 2016), 2016, pp. 439-443.

[30] Avireni Srinivasulu, P. Dipankar, CCII+ based novel waveform generator with grounded resistor/capacitor for tuning, In: proc. of 21st IEEE Applied Electronics International Conference (AEIC-2016), 2016, pp. 247-252.