REALIZATION OF ANALOG SIGNAL PROCESSING MODULES USING CARBON NANOTUBE FIELD EFFECT TRANSISTORS

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ABSTRACT

This thesis presents the realization and performance analysis of several carbon nanotube field effect transistor (CNTFET) based analog signal processing (ASP) modules. CNTFET is predicted as a possible successor to conventional silicon complementary metal oxide semiconductor (CMOS), which has reached its scaling limits. The CMOS based ASP modules face significant challenges at deep nanoscale, resulting in severe performance degradations due to short channel effects. The main goal of this work is to realize CNTFET active building blocks (ABBs), and then to utilize these ABBs for realization of low-voltage, low-power, and high-frequency ASP modules. The proposed ABBs have low power dissipation, reduced parasitic components, and minimum number of CNTFETs. The proposed modules are active inductor (AI), first-order phase shifter, and second-order phase shifter. This research proposes a new CNTFET based grounded AI (GAI) circuit with high self-resonance frequency (SRF), wide tunable inductance range, and high quality factor. Simulation results demonstrate that the GAI offers tunable inductance from 4.4 nH to 287.4 nH with a maximum SRF of 101 GHz. It consumes very low power dissipation of 0.337 mW. In comparison to high performance available GAI circuits, the proposed GAI shows 34% reduction in power dissipation and nine times higher SRF. A high-frequency low-noise amplifier (LNA) circuit is also designed by utilizing the proposed GAI to showcase its application. The simulation result shows high frequency bandwidth of 17.5 GHz to 57 GHz, 15.9 dB maximum voltage gain, better than -10 dB input matching, and less than 3 dB noise figure. This research also proposes a compact wideband first-order phase shifter (FOPS) and active-only FOPS (AOFOPS). Simulation results demonstrate the FOPS has a tunable pole frequency range between 1.913 GHz and 40.2 GHz, input and output voltage noises of 4.402 nV/$\sqrt{Hz}$ and 4.414 nV/$\sqrt{Hz}$ respectively, and power dissipation of 0.4862 mW. The AOFOPS circuit also offers a wide tunable range of pole frequency between 34.2 GHz to 56.4 GHz with input noise and output noise of 6.822 nV/$\sqrt{Hz}$ and 6.761 nV/$\sqrt{Hz}$ respectively, and power dissipation of only 0.0338 mW. The AOFOPS dissipates 12.40 times less power in comparison to state-of-art FOPS circuits. This work also proposes active-only second-order phase shifter. The proposed circuit provides a tunable pole frequency between 16.2 GHz to 42.5 GHz, with input and output noises of 21.698 nV/$\sqrt{Hz}$ and 21.593 nV/$\sqrt{Hz}$ respectively, while consuming 0.2256 mW power. All circuit performances are verified through HSPICE simulation by utilizing the Stanford CNTFET model at 16 nm technology node with supply voltage of 0.7 V.

ABSTRAK

Tesis ini membentangkan realisasi dan analisis prestasi beberapa modul pemprosesan isyarat analog (ASP) berasaskan transistor kesan medan nanotiub karbon (CNTFET). CNTFET diramalkan sebagai pengganti kepada semikonduktor oksida logam pelengkap (CMOS) silikon lazim, yang sudah mencapai had penskalaannya. Modul ASP CMOS menghadapi cabaran besar pada skala-nano dalam, yang menyebabkan kemerosotan prestasi yang teruk kerana kesan saluran pendek. Tujuan utama kerja ini adalah untuk merealisasi blok binaan aktif (ABB), dan kemudiannya digunakan untuk merealisasi modul ASP voltan-rendah dan kuasa-rendah yang berfrekuensi tinggi. ABB yang dicadangkan mempunyai pelesapan kuasa yang rendah, kebolehtalaan yang tinggi, pengurangan komponen parasit, dan menggunakan bilangan CNTFET yang minimum. Modul yang dicadangkan adalah induktor aktif (AI), penganjak fasa tertib-pertama, dan penganjak fasa tertib-kedua. Penyelidikan ini mencadangkan litar AI terbumi (GAI) CNTFET yang baharu yang mempunyai ciri-ciri frekuensi swaresonans (SRF) yang tinggi, kearuhan yang boleh ditala dalam julat yang lebar, dan faktor kualiti yang tinggi. Hasil simulasi menunjukkan bahawa litar GAI menawarkan aruhan boleh ditala dari 4.4 nH hingga 287.4 nH dengan SRF maksimum 101 GHz. Ia melesapkan kuasa yang sangat rendah iaitu 0.337 mW. Berbandingkan dengan litar GAI berprestasi tinggi sedia ada, GAI yang dicadangkan menunjukkan pengurangan pelesapan kuasa sebanyak 34% dan peningkatan SRF sembilan kali lebih tinggi. Litar penguat rendah-hingar (LNA) berfrekuensi tinggi juga direka bentuk berdasarkan GAI yang dicadangkan untuk menunjukkan pengaplikasiannya. Hasil simulasi menunjukkan lebar jalur frekuensi yang tinggi iaitu 17.5 GHz hingga 57 GHz, gandaan voltan maksimum 15.9 dB, padanan input melebihi -10 dB, dan angka hingar kurang dari 3 dB. Penyelidikan ini juga mencadangkan penganjak fasa tertib-pertama (FOPS) dan FOPS hanya-aktif (AOFOPS). Hasil simulasi FOPS menunjukkan julat frekuensi kutub yang boleh diatur antara 1.913 GHz dan 40.2 GHz, hingar voltan masukan dan voltan keluaran masing-masing 4.402 nV/$\sqrt{Hz}$ dan 4.414 nV/$\sqrt{Hz}$, dan pelesapan kuasa 0.4862 mW. Litar AOFOPS ini juga menawarkan frekuensi kutub yang dapat ditala dengan luas antara 34.2 GHz hingga 56.4 GHz dengan hingar masukan dan hingar keluaran masing-masing 6.822 nV/$\sqrt{Hz}$ dan 6.761 nV/$\sqrt{Hz}$ dan pelepasan kuasa hanya 0.0338 mW. Litar AOFOPS yang dicadangkan dapat mengurangkan pelesapan kuasa sebanyak 12.40 kali berbanding litar FOPS terkini. Penyelidikan ini juga mencadangkan penganjak fasa hanya-aktif tertib-kedua. Litar yang dicadangkan menyediakan frekuensi kutub yang dapat ditala antara 16.2 GHz hingga 42.5 GHz, dengan hingar masukan dan hingar keluaran masing-masing 21.698 nV/$\sqrt{Hz}$ dan 21.593 nV/$\sqrt{Hz}$, dan penggunaan kuasa 0.2256 mW. Semua prestasi litar disahkan melalui simulasi HSPICE yang menggunakan model CNTFET Stanford pada nod teknologi 16 nm dengan bekalan kuasa 0.7 V.

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LIST OF ABBREVIATIONS

ABBs	-	Active Building Blocks
AI	-	Active Inductor
AOFOPS	-	Active Only First Order Phase Shifter
AOSOPS	-	Active Only Second Order Phase Shifter
ASP	-	Analog Signal Processing
CG	-	Common Gate
CMOS	-	Complementary Metal Oxide Semiconductor
CNTFET	-	Carbon Nanotube Field Effect Transisitor
CS	-	Common Source
DSP	-	Digital Signal processing
FOPS	-	First Order Phase Shifter
GAI	-	Grounded Active Inductor
GCS	-	Graphite Cylindrical Sheets
Gyrator-C	-	Gyrator-Capacitance
IC	-	Integrated Circuit
IVB	-	Inverting Voltage Buffer
LNA	-	Low Noise Amplifier
NF	-	Noise Figure
NTE	-	Negative Transconductance Element
OTA	-	Operational Transconductance Amplifier
PTE	-	Positive Transconductance Element
QF	-	Quality Factor
SRF	-	Self Resonance Frequency
VCO	-	Voltage Controlled Oscillator
VCR	-	Voltage Controlled Resistor

LIST OF SYMBOLS

π	-	Pi
Ω	-	Ohm
ω	-	Pole frequency
$\mho$	-	Mho
C_{gs}	-	Gate to source capacitance
dB	-	Decibel
D_T	-	Diameter of CNT
g_{ds}	-	Output conductance
GHz	-	Gigahertz
g_m	-	Transconductance
MHz	-	Megahertz
nH	-	Nanohenry
nm	-	Nanometer
N_T	-	Number of CNTs
S_T	-	CNT pitch

CHAPTER 1

INTRODUCTION

1.1 Background

For future data processing and high speed telecommunication solutions, analog signal processing (ASP) techniques are considered as a promising alternative to digital signal processing (DSP) techniques, as analog devices outperform their digital-counterparts in terms of power dissipation, cost and the maximum achievable bandwidth [1]. Thus, ASP modules are considered as unavoidable and significant component of system on chip. They play vital role in a variety of high-performance applications such as a low noise amplifier (LNA) [2], continuous time filters [3], voltage controlled oscillators (VCOs) [4] and phase shifters [5].

Due to persistent focus on Moore's law transistor scaling and continuous technological advancements, complementary metal oxide semiconductor (CMOS) based ASP modules are prominent in the last four decades. However, reduction of channel length below 32 nm complicates designing for present CMOS technologies due to short channel effects, increased leakage current, decreased gate control and sensitivity to process variations in integrated circuit (IC) manufacturing [6]. Therefore, it is extremely imperative for IC industry to explore new materials as well as devices that equally works well for more-than-Moore technologies and beyond CMOS as coined by International Roadmap for Devices and Systems (IRDS) [7, 8]. The latest report by IRDS for 2021 [8] predicts that CNTFET is a possible replacement for CMOS technology from 2025 onwards.

To find replacements for CMOS technology, many devices and techniques are introduced and evaluated by researchers such as double gate field effect transistor (FET), single electron transistor, fin FET and carbon nanotube FET (CNTFET) [9]. Among these solutions, CNTFETs are considered front runners for further continuation of scaling down the feature length and extension of the saturated Moore's law [8, 10, 11]. Since the operational principle and the device structure of CNTFET is similar to CMOS device, it is possible that CNTFET can use efficiently the existing CMOS design infrastructure and CMOS fabrication process [12].

Since CNTFET introduction as an alternative for CMOS technology, circuit level realization in the digital domain has been demonstrated by many researchers; however, limited works have been done on the design and analysis of CNTFET based ASP modules [13]. This unexplored territory of CNTFET based ASP modules opens a new research area, which needs to be explored for the future demands of ASP applications in nanometer regime. For IC designers, the cost and integration of ASP chip for smaller chip area, low power dissipation and larger bandwidth are emerging issues. The recent push towards 5G/6G communication systems and other similar applications further aggravate these design challenges [14].

Inductors are important components that play a key role in the design of these ASP modules. Majority of ASP modules utilizes on-chip passive spiral inductors. However, spiral inductor faces several disadvantages like larger chip area, low and fixed inductance, low self-resonance frequency (SRF), low quality factor (QF) and incompatibility with low-cost standard semiconductor process [15, 16]. In consequence, the use of active inductors (AIs) instead of passive spiral inductors improve the design of ASP modules by reducing the cost and size of chips [16]. Moreover, the tunability of AI further improves the design of these modules and helps designers to adapt specifications for different ASP applications. However, the design of AI with low power dissipation, large inductive bandwidth, large inductance magnitude and high QF is a challenging task. If these design challenges are solved, the applications of AI will be expanded in the development of several other ASP modules such as VCO, LNA, power dividers and frequency selective filters.

State-of-the-art continuous time signal processing applications utilize one or more types of ASP module, as it is not possible to use a single type of module to cater for the needs of different systems with diversified inputs/outputs. Figure 1.1 demonstrates an example of beamforming scheme where different types of ASP module are utilized for their intended goals [17]. Like AI, phase shifter is another important multipurpose ASP module that functions as a fundamental building block of many analog signal processors [18]. It finds applications in the realization of various high-Q frequency selective circuits, beamforming, radar systems as well as oscillators [19, 20]. Design of area efficient, low voltage, low power phase shifter with tunable pole frequency is another challenging task.

ASP modules are mostly based on different active building blocks (ABBs) that best suit the desired applications. Design of AI and phase shifter for broadband high frequency applications is a very challenging task, especially when dealing with CNTFET based ABBs. For high frequency applications, ABBs are very sensitive to device parasitics and their power dissipation may affect the performance of desired ASP module [21]. Thus realization/selection of an efficient active device that contributes less parasitics and low power dissipation to the ASP module is a crucial requirement.

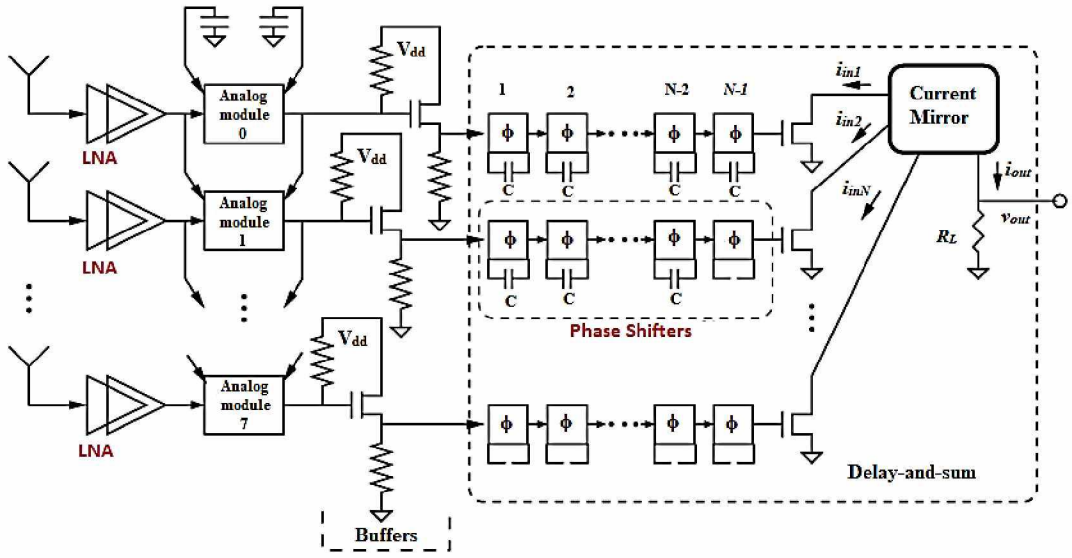

Figure 1.1 Beamforming scheme [17]

The system design of CNTFET based ASP modules for multipurpose high frequency broadband applications must provide desired functionality with improved performance, reduced active and passive devices, and minimize parasitic effect by choosing suitable and efficient topology.

1.2 Problem Statement

Designing low voltage, low power CNTFET based ASP modules for broadband high frequency applications is not a straightforward task, as performance of an ASP module is very much dependent on high frequency parasitic effects [21, 22]. The first crucial requirement in the design of such ASP module is to explore different application specific ABBs, which provide low power consumption, lower parasitic design effects, large signal bandwidth and arithmetic operation capability.

In design of ASP modules for high frequency applications, non-ideal port parasitics of used ABBs ultimately increase the design complexity of the modules and also impose serious frequency limitations on the operation and performance [22, 16]. These limitations can be minimized by realization of efficient circuit topology during the design phase of specific ASP module. Moreover, selection of the most appropriate CNTFET design parameters (inter CNT pitch, CNT diameter/chirality vector and number of CNTs) is another critical task of the design phase [6, 10-12].

ABB based AI with high inductance, high SRF, high tunability within an acceptable QF are the most challenging tasks for high frequency broadband applications [23]. Tunability of AI is an important feature that enables designers to adapt specification of different broadband applications. This desirable feature helps in the frequency band selection of filters, VCOs and so many other applications [5, 15, 24-31]. Many recently published high QF AI topologies do not have tunability feature [32-34]. Thus, these AIs are not suitable for broadband applications and can be used only for specific applications with fixed inductance and QF value. High inductance AI with acceptable QF is another important requirement [25]. In RF

circuits such as LNA, high inductance is necessary for high gain as LNA gain is dependent on magnitude of output inductance [23].

Although most AI circuit topologies presented to date are compact and achieve acceptably larger QF than its spiral counterpart, their application in low voltage, low power broadband ASP modules has been limited because of their narrow inductive bandwidth [35-46]. As a result, to the best of our knowledge, no AI circuit topology has been utilized for a high frequency (> 11 GHz) and wideband (> 7 GHz bandwidth) ASP module [47]. This comparatively narrow inductive bandwidth ultimately excludes AI for the design of broadband high frequency ASP modules.

For flexibility, the pole frequency of a phase shifter should be widely tunable. Tunability of pole frequency enables a phase shifter to be used in broadband applications [48, 49]. Low power dissipation of a phase shifter can be obtained by minimizing number of active and passive devices [50]. Moreover, the ABB power dissipation will be added to the total phase shifter power consumption, so use of ABB with less power dissipation is needed.

Based on AI and phase shifter examples, in summary, the design challenges involve low power dissipation, high tunability, minimization of parasitic components (which degrade high frequency performance) and selection of appropriate CNTFET design parameters (inter CNT pitch, CNT diameter/chirality vector and number of CNTs). In addition, high SRF and highly tunable AI with acceptable QF are other research challenges.

1.3 Research Objectives

The objectives of this research work are:

i. To design CNTFET based ABBs suitable for the realization of low power and high frequency ASP modules. These ABBs are inverting voltage buffer (IVB), negative transconductance element (NTE) and positive transconductance element (PTE). The ASP modules to be realized using designed ABBs are AI, first order phase shifter (FOPS) and second order phase shifter (SOPS). The CNTFET ABBs are targeted to operate up to 100 GHz and with less then 1 mW power dissipation.

ii. To design CNTFET based AI circuit topology for high frequency broadband applications. The AI circuit will be realized using the designed ABBs to achieve high QF, high tunable inductance, high SRF and low power dissipation. The target performance is for the AI circuit to be inductive up to 100 GHz with a power dissipation less than 1 mW.

iii. To design CNTFET based FOPS and SOPS topologies for high frequency applications. The phase shifter circuits will be realized using the designed ABBs to achieve large tunable pole frequency with less than 1 mW power dissipation.

1.4 Scope and Limitations

The major scope and limitations of this research work are as follows:

i. This study is mainly concerned with the design of ASP modules for high frequency broadband applications using CNTFET ABBs. These modules only include CNTFET based AI and phase shifters.

ii. HSPICE simulation tool will be used for design and analysis of ABB and the ASP modules. This work will be purely based on simulation at transistor level due to the unavailability of CNTFET circuit fabrication facility.

iii. Stanford CNTFET model at 16 nm technology node will be utilized for design of AI and phase shifter circuits.

1.5 Research Contributions

Contributions of this thesis are listed as follows:

i. The first contribution of this work is the proposal for a new compact CNTFET based ABB known as PTE. Circuit analysis shows that the proposed ABB is a suitable candidate for low voltage, low power broadband applications, with voltage supply as low as 0.7 V and power dissipation in the uW range.

ii. The second contribution of this research work is proposal for CNTFET based grounded AI (GAI) circuit. The GAI was designed and simulated using 16 nm CNTFET technology node using HSPICE. Simulation results demonstrate that realized GAI circuit offers high tunable inductance from 4.4 nH to 287.4 nH with a maximum SRF of 101 GHz. It offers low power dissipation of 0.337 mW. Tunability of the GAI has been achieved by utilizing CNTFET varactor. A broadband LNA circuit was also designed and simulated by utilizing the proposed GAI topology. The simulation result shows very high frequency bandwidth of 17.5 GHz to 57 GHz and dissipates 6.961 mW from 0.7 V supply. Moreover, the GAI based LNA provides a 15.9 dB maximum gain. In addition, better than -10 dB input matching and less than 3 dB noise figure (NF) over the entire bandwidth is observed.

iii. The third contribution of this research is the proposal for a compact wideband FOPS using CNTFET based Inverting Voltage Buffer (IVB) and Voltage Controlled Resistor (VCR). Simulation results demonstrate a tunable pole frequency range between 1.913 GHz and 40.2 GHz with input and output voltage noises of 4.402 $nV/\sqrt{Hz}$ and 4.414 $nV/\sqrt{Hz}$ respectively, and power dissipation of 0.4862 mW.

iv. The fourth contribution of this research is the design of an active only first order phase shifter (AOFOPS) using IVB and CNTFET varactor. The active only circuit topology offers a wide tunable range of pole frequency between 34.2 GHz to 56.4 GHz. Simulation results show that the equivalent input noise and output noise for the realized all active phase shifter at a designed pole frequency of 49.26 GHz are 6.822 $nV/\sqrt{Hz}$ and 6.761 $nV/\sqrt{Hz}$ respectively, while it dissipates 0.0338 mW.

v. The fifth contribution of this research is the design of an active only second order phase shifter (AOSOPS) by utilizing two negative transconductance elements (NTE), one PTE, two varactors and one VCR. The AOSOPS topology provides a tunable pole frequency between 16.2 GHz to 42.5 GHz with input and output noise of 21.698 $nV/\sqrt{Hz}$ and 21.593 $nV/\sqrt{Hz}$ respectively. The power dissipation of AOSOPS is 0.2256 mW.

1.6 Thesis Organization

This dissertation is organized into seven chapters. Chapter 1 discusses the background, problem statement, objectives and scope of this research work. Moreover, this chapter also highlights the contributions of this research work.

Chapter 2 of this dissertation provides a summary of advanced AI and phase shifter circuit topologies available in the open literature. The performance of these available ASP modules is discussed and investigated thoroughly.

Chapter 3 of this thesis discusses the methodology adopted in this research work. Moreover, the flow of the complete design process steps is discussed thoroughly for the realization of CNTFET ABBs and ASP modules.

Chapter 4 introduces the proposed GAI circuit. The GAI equivalent parasitic model will be explained in this chapter. Also, equations for inductance and QF will be analyzed. Simulation results of the GAI topology will also be explained thoroughly. Moreover, the application of the proposed GAI in the design of broadband LNA will be demonstrated.

Chapter 5 introduces the proposed FOPS topologies. The realized circuit description, analysis and simulation results will be explained in this chapter. Moreover, a brief comparison of the proposed circuits with other available FOPS topologies in the open literature will be discussed.

Chapter 6 introduces the AOSOPS circuit. The proposed AOSOPS circuit design and simulation results are discussed in this chapter. In addition, a comparison study with other SOPS circuits is conducted and discussed. Lastly, the conclusion and recommendations for further research is presented in Chapter 7.

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LIST OF PUBLICATIONS

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