Beiträge aus der Informationstechnik

Manu Viswambharan Thayyil

Analysis and Design of Silicon based Integrated Circuits for Radio Frequency Identification and Ranging Systems at 24 GHz and 60 GHz Frequency Bands

VOGT

Dresden 2023

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.dnb.de abrufbar.

Bibliographic Information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.dnb.de.

Zugl.: Dresden, Techn. Univ., Diss., 2023

Die vorliegende Arbeit stimmt mit dem Original der Dissertation „Analysis and Design of Silicon based Integrated Circuits for Radio Frequency Identification and Ranging Systems at 24 GHz and 60 GHz Frequency Bands“ von Manu Viswambharan Thayyil überein.

Gesetzt vom Autor

ISBN 978-3-95947-067-4

Jörg Vogt Verlag
Niederwaldstr. 36
01277 Dresden
Germany

Phone: +49-(0)351-31403921
Telefax: +49-(0)351-31403918
e-mail: info@vogtverlag.de
Internet : www.vogtverlag.de

Technische Universität Dresden

Analysis and Design of Silicon based Integrated Circuits for Radio Frequency Identification and Ranging Systems at 24 GHz and 60 GHz Frequency Bands

M.Sc.
Manu Viswambharan Thayyil

der Fakultät Elektrotechnik und Informationstechnik
der Technischen Universität Dresden

zur Erlangung des akademischen Grades

Doktoringenieur

(Dr.-Ing.)

genehmigte Dissertation

Vorsitzender:	Prof. Dr.-Ing. habil. Wolf-Joachim Fischer
Gutachter:	Prof. Dr. sc. techn. habil. Dipl. Betriebswiss. Frank Ellinger
	Prof. Dr.-Ing. habil. Alexander Kölpin

Tag der Einreichung: 09. Januar 2023
Tag der Verteidigung: 08. Juni 2023

What I cannot create, I do not understand.

Richard P. Feynman

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Acknowledgements

First and foremost I would like to thank Prof. Dr. sc. techn. habil. Frank Ellinger for the trust bestowed in me and providing the opportunity to do the doctoral work at the chair for circuit design and network theory, TU Dresden.

My special thanks to Dr. Niko Joram for mentorship through his actions and timely directions. His work on local positioning systems has always been an inspiration to acquire the multidisciplinary skills required for building reliable systems and has gone a long way into the making of this thesis. I would also like to appreciate his effort in reviewing this work and other publications which have remarkably improved their quality. I would also like to give a special thanks Dr. Stefan Schumann for support in the laboratory.

I am grateful for having shared an office with wonderful colleagues like Songhui Li - the Shifu, Amirali Taghavi, Dr. Adrian Figueroa, Florian Protze and Marco Gunia. Thanks to them for creating a stimulating and open work atmosphere. I would also like to thank other colleagues and students whom I was privileged to collaborate with: Seyyedmohsen Seyyedrezaei, Mengqi Cui, Jan Pliva, Dr. Tilo Meister, Sujay Charania, Dr. Naglaa Elagroudy, Dr. Hatem Ghaleb, Dr. Belal Al-Quidsi, Zoltán Tibenszky and Katharina Isaack.

A humbling thank you goes to all those who have inspired, provided opportunity, been kind, respectful and considerate to pave me small steps along the way in this journey, including: Vinodkumar A.N., Marykutty T., Dr. Kasyap T.V., Bella Jacob, Vishnu Mohan, Prince V. Thachil, Biju Mathew, Dr. M. V. Rajesh , Dr. T.K. Mani, Shalu Thomas, Dr. Kurian Polachan, Kurian John, B. Manojkumar, Vinodh Rakesh, Anil K. S. Dr. Thirukumar Vethanayagam and Frank Dolzmann.

Last but not the least, boundless gratitude to my family for lending me their valuable time and support so that I could realize this work.

Dresden, im Januar 2023 *Manu Viswambharan Thayyil*

Abstract

This scientific research work presents the analysis and design of radio frequency (RF) integrated circuits (ICs) designed for two cooperative RF identification (RFID) proof of concept systems. The first system concept is based on localizable and sensor-enabled superregenerative transponders (SRTs) interrogated using a 24 GHz linear frequency modulated continuous wave (LFMCW) secondary radar. The second system concept focuses on low power components for a 60 GHz continuous wave (CW) integrated single antenna frontend for interrogating close range passive backscatter transponders (PBTs).

In the 24 GHz localizable SRT based system, a LFMCW interrogating radar sends a RF chirp signal to interrogate SRTs based on custom superregenerative amplifier (SRA) ICs. The SRTs receive the chirp and transmit it back with phase coherent amplification. The distance to the SRTs are then estimated using the round trip time of flight method. Joint data transfer from the SRT to the interrogator is enabled by a novel SRA quench frequency shift keying (SQ-FSK) based low data rate simplex communication. The SRTs are also designed to be roll invariant using bandwidth enhanced microstrip patch antennas. Theoretical analysis is done to derive expressions as a function of system parameters including the minimum SRA gain required for attaining a defined range and equations for the maximum number of symbols that can be transmitted in data transfer mode. Analysis of the dependency of quench pulse characteristics during data transfer shows that the duty cycle has to be varied while keeping the on-time constant to reduce ranging errors. Also the worsening of ranging precision at longer distances is predicted based on the non-idealities resulting from LFMCW chirp quantization due to SRT characteristics and is corroborated by system level measurements.

In order to prove the system concept and study the semiconductor technology dependent factors, variants of 24 GHz SRA ICs are designed in a 130 nm silicon germanium (SiGe) bipolar complementary metal oxide technology (BiCMOS) and a partially depleted silicon on insulator (SOI) technology. Among the SRA ICs designed, the SiGe-BiCMOS ICs feature a novel quench pulse shaping concept to simultaneously improve the output power and minimum detectable input power. A direct antenna drive SRA IC based on a novel stacked transistor cross-coupled oscillator topology employing this concept exhibit one of the best reported combinations of minimum detected input power level of −100 dBm and output power level of 5.6 dBm, post wirebonding. The SiGe stacked transistor with base feedback capacitance topology employed in this design is analyzed to derive parameters including the SRA loop gain for design optimization. Other theoreti-

cal contributions include the analysis of the novel integrated quench pulse shaping circuit and formulas derived for output voltage swing taking bondwire losses into account. Another SiGe design variant is the buffered antenna drive SRA IC having a measured minimum detected input power level better than −80 dBm, and an output power level greater than 3.2 dBm after wirebonding. The two inputs and outputs of this IC also enables the design of roll invariant SRTs. Laboratory based ranging experiments done to test the concepts and theoretical considerations show a maximum measured distance of 77 m while transferring data at the rate of 0.5 symbols per second using SQ-FSK. For distances less than 10 m, the characterized accuracy is better than 11 cm and the precision is better than 2.4 cm. The combination of the maximum range, precision and accuracy are one of the best reported among similar works in literature to the author's knowledge.

In the 60 GHz close range CW interrogator based system, the RF frontend transmits a continuous wave signal through the transmit path of a quasi circulator (QC) interfaced to an antenna to interrogate a PBT. The backscatter is received using the same antenna interfaced to the QC. The received signal is then amplified and downconverted for further processing. To prove this concept, two optimized QC ICs and a downconversion mixer IC are designed in a 22 nm fully depleted SOI technology. The first QC is the transmission lines based QC which consumes a power of 5.4 mW, operates at a frequency range from 56 GHz to 64 GHz and occupies an area of 0.49 mm^2. The transmit path loss is 5.7 dB, receive path gain is 2 dB and the tunable transmit path to receive path isolation is between 20 dB and 32 dB. The second QC is based on lumped elements, and operates in a relatively narrow bandwidth from 59.6 GHz to 61.5 GHz, has a gain of 8.5 dB and provides a tunable isolation better than 20 dB between the transmit and receive paths. This QC design also occupies a small area of 0.34 mm^2 while consuming 13.2 mW power. The downconversion is realized using a novel folded switching stage down conversion mixer (FSSDM) topology optimized to achieve one of the best reported combination of maximum voltage conversion gain of 21.5 dB, a factor of 2.5 higher than reported state-of-the-art results, and low power consumption of 5.25 mW. The design also employs a unique back-gate tunable intermediate frequency output stage using which a gain tuning range of 5.5 dB is attained. Theoretical analysis of the FSSDM topology is performed and equations for the RF input stage transconductance, bandwidth, voltage conversion gain and gain tuning are derived. A feasibility study for the components of the 60 GHz integrated single antenna interrogator frontend is also performed using PBTs to prove the system design concept.

Kurzfassung

In dieser wissenschaftlichen Forschungsarbeit werden die Analyse und der Entwurf von integrierten Schaltungen (integrated circuits, ICs) für zwei kooperative Radiofrequenzidentifikationssysteme (RFID systems) vorgestellt, die als Konzeptnachweis dienen. Das erste Systemkonzept basiert auf ortbaren und sensorfähigen superregenerativen Transpondern (SRTs), die mit einem 24 GHz-Sekundärradar mit linearer frequenzmodulierter Dauerstrichwelle (linear frequency modulated continuous wave, LFMCW) abgefragt werden. Das zweite Systemkonzept konzentriert sich auf Komponenten mit geringem Stromverbrauch für ein integriertes 60 GHz-Frontend zur Abfrage von passiven Transpondern (passive backscatter transponders, PBTs).

Bei dem 24 GHz SRT-System sendet ein LFMCW-Abfrageradar ein hochfrequentes Rampensignal, um SRTs abzufragen, die auf dafür optimierten Verstärkerschaltungen (super-regenerative amplifiers, SRA) basieren. Die SRTs empfangen das Rampensignal und senden es phasenkohärent und verstärkt zurück. Die Entfernung zu den SRTs wird dann nach der Round-Trip-Time-of-Flight-Methode geschätzt. Die gleichzeitige Datenübertragung vom SRT zum Abfragesystem wird durch eine neuartige Frequenzmodulation (SRA quench frequency shift keying, SQ-FSK) mit niedriger Datenrate ermöglicht. Die SRTs sind mit Hilfe von bandbreitenerweiterten Mikrostreifen-Patchantennen auch rollinvariant konzipiert. Durch eine theoretische Analyse werden mathematische Zusammenhänge in Abhängigkeit der Systemparameter abgeleitet, einschließlich der minimalen SRA-Verstärkung, die zum Erreichen einer bestimmten Reichweite erforderlich ist, sowie Gleichungen für die maximale Anzahl von Symbolen, die im Datenübertragungsmodus übertragen werden können. Die Analyse der Quenchpulse während der Datenübertragung zeigt, dass das Tastverhältnis variiert und die Einschaltdauer konstant gehalten werden muss, um Fehler bei der Abstandsmessung zu reduzieren. Auch die Verschlechterung der Entfernungsgenauigkeit bei größeren Entfernungen auf der Grundlage der ermittelten Nicht-Idealitäten vorhergesagt. Diese ergeben sich aus der Quantisierung des Rampensignals aufgrund der SRT-Eigenschaften. Die Theorie wird durch Systemtests bestätigt.

Um das Systemkonzept zu prüfen und die von der Halbleitertechnologie abhängigen Faktoren zu untersuchen, wurden Varianten der 24 GHz-SRA-ICs in einer 130nm Silizium-Germanium-Technologie (SiGe) mit komplementärem Metalloxidhalbleiter (complementary metal oxide semiconductor, CMOS) und einer 45nm-Silizium-auf-Isolator-Technologie (silicon on insulator, SOI) realisiert.

Unter den entworfenen SRA-ICs zeichnen sich die SiGe-BiCMOS-ICs durch ein neuartiges Quench-Pulse-Shaping-Konzept aus, das gleichzeitig die Ausgangsleistung und die minimale detektierbare Eingangsleistung verbessert. Ein SRA-IC mit direkter Antennensteuerung, der auf einer neuartigen kreuzgekoppelten Oszillatortopologie mit gestapelten Transistoren basiert und dieses Konzept anwendet, weist eine der besten Kombinationen von minimalem detektiertem Eingangsleistungspegel von -100 dBm und einem Ausgangsleistungspegel von 5,6 dBm nach dem Drahtbonden auf. Die genannte Topologie verwendet eine Rückkopplungskapazität an der Basis. Sie wird theoretisch analysiert, um Parameter einschließlich der SRA-Schleifenverstärkung für eine Entwurfsoptimierung abzuleiten. Weitere theoretische Beiträge umfassen die Analyse der neuartigen integrierten Pulsformungsschaltung für die Quench-Pulse und Formeln für den Ausgangsspannungshub unter Berücksichtigung der Bonddrahtverluste. Eine weitere SiGe-Design-Variante ist der gepufferte SRA-IC mit Antennentreiber mit einem gemessenen minimalen detektierten Eingangsleistungspegel von weniger als -80 dBm und einem Ausgangsleistungspegel von mehr als 3,2 dBm nach dem Drahtbonden. Die zwei Ein- und Ausgänge dieses ICs ermöglichen, in Kombination mit der entworfenen Patchantenne, den Aufbau rollinvarianter SRTs. Laborexperimente zur Überprüfung der Konzepte und theoretische Überlegungen zeigen eine maximal gemessene Reichweite von 77 m bei einer Datenübertragungsrate von 0,5 Symbolen pro Sekunde mit SQ-FSK. Bei Entfernungen von weniger als 10 m ist die gemessene Genauigkeit besser als 11 cm und die Präzision besser als 2,4 cm. Die Kombination aus maximaler Reichweite, Präzision und Genauigkeit ist nach Kenntnis des Autors eine der besten, die unter ähnlichen Arbeiten in der Literatur zu finden sind.

Beim entworfenen 60-GHz-CW-Abfragesystem für den Nahbereich sendet das HF-Frontend ein Dauerstrichsignal über einen Quasizirkulator (quasi circulator, QC) im Sendepfad. Dieser ist mit einer Antenne verbunden, um einen PBT abzufragen. Die Rückstreuung wird über den Zirkulator mit der gleichen Antenne empfangen. Das empfangene Signal wird dann verstärkt und zur weiteren Verarbeitung heruntergemischt. Um dieses Konzept zu prüfen, wurden zwei dafür optimierte QC-ICs und ein Abwärtsmischer-IC in einer 22 nm SOI-Technologie realisiert. Der erste auf Streifenleitungen basierende QC benötigt eine Versorgungsleistung von 5,4 mW, arbeitet in einem Frequenzbereich von 56-64 GHz und nimmt eine Chipfläche von 0.49 mm^2 ein. Der Verlust im Sendepfad beträgt 5,7 dB, die Verstärkung im Empfangspfad 2 dB und die abstimmbare Isolation zwischen Sende- und Empfangspfad liegt zwischen 20 dB und 32 dB. Der zweite QC basiert auf konzentrierten Elementen, arbeitet in einer relativ schmalen Bandbreite von 59,6 GHz bis 61,5 GHz, hat eine Verstärkung von 8,5 dB und bietet eine abstimmbare Isolation von mehr als 20 dB zwischen dem Sende- und Empfangspfad. Dieser QC-Entwurf benötigt außerdem nur eine kleine Fläche von 0.34 mm^2 und hat eine Leistungsaufnahme von 13,2 mW. Das Abwärtsmischen wird mit einer neuartigen Topologie mit gefalteten Schaltstufen (folded switching stage down conversion mixer, FSSDM) realisiert. Die Topologie ist so optimiert, dass sie eine maximale Spannungsverstärkung von 21,5 dB bei nur 5,25 mW Leistungsaufnahme erreicht. Es handelt sich dabei nach Kenntnis des Autors um eine der besten Kombinationen aus Spannungsverstärkung und Leistungsaufnahme in der aktuellen Literatur. Die Spannungsverstärkung der Schaltung ist um den Faktor 2,5 höher als der Stand der Technik.

Der Entwurf verwendet auch eine einzigartige, durch das Backgate abstimmbare Zwischenfrequenz-Ausgangsstufe, mit der ein Verstärkungsabstimmungsbereich von 5,5 dB erreicht wird. Die theoretische Analyse der FSSDM-Topologie wird durchgeführt, und es werden Gleichungen für die Transkonduktanz der Eingangsstufe, die Bandbreite, die Spannungsumwandlungsverstärkung und den Verstärkungsabstimmungsbereich abgeleitet. Um den Systementwurf zu überprüfen wird eine Machbarkeitsstudie für die Komponenten des 60 GHz-Abfragefrontends mit Einzelantennen unter Verwendung von PBTs durchgeführt.

Contents

1 Introduction

1.1 Motivation and Related Work

Throughout human history, the ability to identify objects and determine their position in space has been a skill of utmost importance. This skill was necessary for tasks including navigation of surroundings, locating objects and following animals, thus making it as essential as communication and time telling [PMvD+20]. A wide range of tools and techniques like coordinate systems, maps, references based on the motion of celestial bodies and compasses were invented in due course to master this ability. Foundations to alter those conventional paradigms beyond recognition were laid in the second half of 19^{th} century through exponential advances in our understanding of electromagnetic (EM) radiant energy, when its existence and characteristics were predicted as fundamental laws in the seminal works of J.C. Maxwell [Max65], and conclusive proof of its existence was obtained through experiments done by H. R. Hertz [WC95, SSP14]. Building on their work, pioneers including J.C. Bose, A. Popov, G. Marconi, R. Fessenden, E.H. Armstrong, J.L. Baird and many others sought to find a diverse set of applications for electromagnetism [Eme97, Bon98, SSP14]. Their work done in that era form the building blocks upon which many fascinating and now ubiquitous technologies including radio communications, *radio detection and ranging* or radar and radio frequency identification (RFID) are based.

Originally devised for direction finding [Sch11] and prevention of ship collisions [Sko88, SSP14], the radar concept for detection of objects and range estimation based on the reflection of EM waves evolved independently across multiple countries in the early 20^{th} century, with significant contributions from inventors including C. Hülsmeyer with the spark-gap based *telemobiloskop* [Sko88], R. Watson-Watt with the 22 MHz Chain Home [SSP14] and U. Tiberio with the radar equation for the linear frequency modulated continuous wave (LFMCW) radar *radiotelemetro* at 200 MHz [Gal14]. Since then, radar technology has been used in a diverse range of systems including precise localization systems, imaging systems and also as interrogators in RFID systems.

In RFID systems, a cooperating target [SFS11] also called a transponder or tag communicates with an interrogating radar using backscatter [Lan05]. These systems, which originated as identify friend or foe (IFF) systems and grew from the works of H. Stockman [Sto48], R. F. Harrington [Har64] and others, have a history which runs concurrently with radar systems research [Ros14, Lan05].

Though early radar systems operated at very high frequency (VHF) and ultra high frequency (UHF), the invention of devices like Magnetron and Klystron pushed the frequencies to the microwave band where the highly directive and physically small antennas made the systems long range and more compact [Sko88]. Subsequent advances in semiconductor technology enabled the design of more compact radio frequency (RF) circuits and systems, mainly through discrete components made using III-V compound semiconductor technologies like gallium-arsenide and indium-phosphide [MBG+96, GRB+00]. But recent progress in the highly scalable and integratable silicon based technologies like silicon-germanium bipolar complementary metal oxide semiconductor (SiGe-BiCMOS) [RHW+10a] and fully depleted silicon on insulator (FDSOI) [OLC+18] are making the realization of high performance radio frequency integrated circuits (RFICs) and systems operating at microwave, millimeter-wave (mmWave) and beyond, a reality. These state-of-the-art technologies offer fast transistors, passives like capacitors, inductors and transmission lines with a relatively high quality factor. Additional advantages of such technologies also include the possibility to integrate baseband circuits including filters and analog to digital converters (ADCs), powerful microcontrollers (μCs) and efficient digital signal processing hardware for the implementation of smart algorithms.

These advances have resulted in the miniaturization and scaling of both secondary radar interrogators and RFID transponders, and the creation of ingenious civilian and humanitarian applications like search and rescue, logistics, transportation, public infrastructure, automotive systems. Of particular interest for active transponder based systems are civilian automotive applications and wireless sensor node (WSN) nodes for internet of things (IoT), catering to diverse uses cases from automotive safety systems for parking, lane switching and vehicle tagging [RBK+19], to toll collection, livestock tracking and inventory management.

In such recent applications combining fundamental concepts of radar and RFID transponders, it is becoming increasingly necessary for the transponders to interface with sensors and to be localizable at short to medium distances [SFS11], in addition to the basic functionality of identification and communication using backscatter. These transponders can be either another radar sensor node like in secondary radars [GHZ+11, JWSE12], or backscatter transponders [SFS11, Weh10, SCW+13b, NEAE18, MMW+19]. Fig. 1.1 illustrates a general overview of the components of such a system, where a static element called a reader or interrogator sends transmit command signals to a number of low power remote elements called transponders in the forward-link [FM10]. The transponders which interface to various sensors responds to the interrogation signal and sends data back to the interrogator through the return-link. As will be discussed in detail

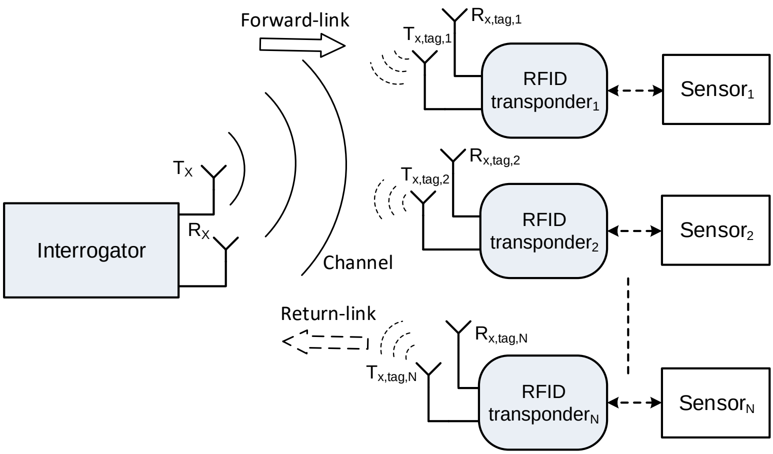

Figure 1.1: System overview showing the components of an RFID system, including an interrogator, antennas and passive or active transponders interfacing sensors.

in Chapter 2, the interrogator and transponders can be implemented in different architectures, technologies and topologies, depending on the usage scenario.

Of the recent RFID transponder based systems and solutions reported for various applications in literature, each has its own unique advantages and also disadvantages. Conventional short range radio and secondary radar based systems like [GHZ+11, JWSE12] where both interrogator and transponders use the same hardware, report location information with high precision, accuracy and long range. They also have communication and multiple sensor interface capabilities. But they are expensive, bulky, consume relatively high power, pose challenges in large scale deployment and operate at relatively low frequencies. Systems based on passive or semi-passive backscatter transponders using Schottky or PIN diodes [MMW+19, MDG12, KPRVH13] are also used for identification and sensor interface at large scale [Lan05]. Though they are inexpensive and consume low power, they operate at near field and are without localization capabilities. Secondary radar interrogator based systems where superregenerative transponders (SRTs) [SFS11, VG08, SCW+13b] are used as cooperative coherent transponders [Bid02] provide a trade-off between the two systems with relatively high precision, accuracy and moderate range. They are also implementable as custom integrated circuits (ICs), making them suitable for mass deployment at moderate costs. But they do not report identification and sensor interfacing capabilities. An important challenge with interrogator frontends operating at frequencies above 24 GHz is that they are bistatic with separate transmit and receive antennas [SCW+13a, MMW+19]. Solutions like transmit (T_x) / receive (R_x) switches are not optimum for RFID and discrete circulators are expensive. Interrogator implementations at such higher frequencies also use discrete commercial components [PD11, SCW+13a, MMW+19] and older technologies with longer minimum feature length, thereby occupying a relatively large area and consume high power [FHB+21, KPRVH13, PKK+11, VHPM+08].

1.2 Scope and Functional Specifications

This work is basic scientific research investigating novel IC topologies and hardware level system design for radio frequency identification and ranging.

The key research questions posed in this thesis are:

Is it possible to reduce energy consumption of integrated microwave RFID transponders that are jointly identifiable and localizable at long ranges? Are such transponders analyzable and implementable using superregenerative amplifier theory?

Are monolithic IC based components consuming very low power at mmWave frequency bands feasible for implementing single antenna RFID interrogators? Is it possible to analyze and understand the characteristics of these components?

To answer these questions, the scope of this work is constrained by the following functional requirement specifications, characteristic of interrogator-transponder systems:

- Proximity, sensitivity & read range: Design of backscatter transponders operating in the range of at least 50 m and within the limits set by the effective isotropic radiated power (EIRP) of the respective frequency bands pose an interesting research problem. This also requires the transponders to have a very high sensitivity to the interrogation signal.

- Localization: Many novel WSN applications require the location of the RFID transponder, preferably with centimeter level accuracy.

- Small form factor: The objects on which transponders are attached should ideally be oblivious to the transponder, and therefore transponders are required to occupy a small area. The same requirement is also applicable for components of the interrogator.

- Low energy consumption: Reducing energy consumption is a key sustainability goal. Hence both transponders and interrogators should be optimized for low power consumption. In particular, the transponders should consume very low energy so that operation from a battery for at least 8 hours is possible.
- Sensor interface, data storage and communication: The transponders should interface with sensors to acquire data of physical parameters, store the data in on-board memory and send the data to the interrogator to emulate WSN nodes.
- Orientation tolerance: It is desirable to have robust detection and localization even if the transponder orientation changes by rolling.
- Interference tolerance & robustness: Interrogators shall detect and measure the distance to transponders with a high degree of robustness showing resilience to interfering frequencies.
- Frequency tolerance: The system should operate in the unlicensed microwave and mmWave frequency bands so that experimental testing is possible without interference with existing off-the-shelf systems.
- Scalability: Scalability and integration are one of the key requirements for all research done in the information era. It is particularly relevant to RFID transponders.

1.3 Objectives and Structure

This thesis presents two system concepts based on RFICs aimed at seeking answers to the key questions posed in Section 1.2 and to create new knowledge in the field of RFID transponders and interrogators. The main focus is on the analysis, design and characterization of two system concepts for identification and ranging at 24 GHz and 60 GHz. The designed systems include a medium range, locatable SRT based system concept at 24 GHz, and a close range, low area, low power interrogator and semi-passive transponder based system concept at 60 GHz.

For the 24 GHz system concept, the emphasis is on the design of custom RFICs in a SiGe-BiCMOS technology for the SRTs. The SRTs are interrogated using a LFMCW secondary radar based interrogator implemented mainly using commercial off-the-shelf (COTS) components and a custom power amplifier (PA) IC for range extension. Exploiting specific characteristics of superregenerative amplifier (SRA) operation, makes the SRTs localizable and sensor-enabled. The SRTs also feature roll invariance using custom bandwidth enhanced microstrip patch antennas.

The 60 GHz system concept focuses on RFICs for an unmodulated continuous wave (CW) radar interrogator frontend. In the CW interrogator frontend of this system, a quasi circulator (QC) IC with an integrated low noise amplifier (LNA) is used to interface both the T_x and R_x signal paths to a single antenna. Novel low power topologies are devised to implement custom QC variants and a down-conversion mixer IC in a FDSOI technology. A passive transponder using custom passive and active elements is used to test this system concept.

Though algorithms are designed for data analysis and range estimation, the focus of this thesis is the analysis, design and characterization of the two systems at hardware level and key RF components at circuit level.

The key contributions from this work are the following:

- System level design: System level requirements are derived from analytic expressions of parameters for both the LFMCW and CW interrogators. Theoretical considerations include minimum SRA gain required for achieving a particular maximum range, and models for simultaneous data transfer and ranging using novel SRA quench frequency shift keying (SQ-FSK). Equations to determine key parameters including the maximum number of symbols that can be transmitted in data transfer mode and SRA gain required to achieve a particular maximum range as a function of system parameters. Parameters serving as requirement specifications for both circuit design are also derived *[TFJE23].

- Integrated circuit design: Circuit analysis, design and characterization of RFICs meeting the system level requirement specifications using novel topologies. The novel designs operating at 24 GHz include SRAs variants with integrated quench pulse shaping to simultaneously maximize the output power, minimize the detected input signal and provide multiple inputs and outputs to implement roll-invariance *[TLJE18, TGJE18, TJE20]. Also implemented is a PA with novel bandwidth extension technique *[TLJE19]. The designs operating at 60 GHz include two low power, low area QCs with single antenna interface *[TPC+21] and a folded switching stage down-conversion mixer (FSSDM) with a high conversion gain to power consumption ratio *[TSJE21].

- Experimental tests: The parameters of the designed RFICs are characterized independently. The RFICs meeting the requirement specifications are employed along with discrete components to implement the two proof of concept systems involving interrogators, SRTs and antennas *[TTCE18]. Measured system level parameters like range and position estimates, data transfer and roll-invariance are analyzed using programs employing a chirp z-transform (CZT) based algorithm and results are compared against simulations and theory.

The rest of this work is organized as follows:

Chapter 2 presents the features and classification of the RFID transponders and interrogators reported in the literature. Key system level specifications are identified to compare and identify the optimum transponder topology and interrogator architecture. Also included are the fundamentals of SRA operation and a brief overview of the semiconductor technologies used for design.

Chapter 3 is dedicated to the design of K-band SRT and LFMCW radar based identification and ranging system. This chapter includes the system level design and derivation of requirement specifications for circuit design, along with the introduction of key design parameters for the use of SRA in range enhanced SRTs. The chapter then proceeds with sections on analysis, design and characterization of the various 24 GHz RFICs used in the system concept, followed by the implementation details of the components of the proof of concept system. These include sections on the SRT, LFMCW secondary radar interrogator, bandwidth enhanced patch antennas and the data analysis algorithm.

Chapter 4 has a similar structure as Chapter 3, and starts with the system level design, and moves on to the analysis, design and characterization of various 60 GHz RFICs and a 60 GHz passive transponder. The chapter ends with sections on the proof of concept system implementation based on passive transponder and CW interrogator operating at V-band.

Chapter 5 follows with the experimental tests of both the proof of concept systems and the corresponding results from laboratory measurements.

Chapter 6 wraps up this thesis with a summary of main results and key contributions, outlook into the future and an overview of open research questions and interesting challenges that lies ahead in the exciting fields of RFICs, RFID transponders and interrogators.