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Analysis and Design of Millimeter-wave Integrated Circuits for Civilian Automotive Radar Applications

Songhui Li

der Fakultät Elektrotechnik und Informationstechnik
der Technischen Universität Dresden
zur Erlangung des akademischen Grades

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Abstract

Civilian automotive radar technology is a hot topic with the growing demand for safe driving and the exploration of autonomous driving technologies. The need for higher-performance radars drives greatly the research on millimeter-wave radars, especially the essential millimeter-wave integrated circuits. This thesis focuses on the analysis and design of integrated circuit blocks for civilian automotive radar applications.

To prove the concepts of the millimeter-wave circuits for civilian automotive radar in the 77 GHz/79 GHz frequency band, chips were implemented in a 22 nm FD-SOI CMOS technology. The realization of millimeter-wave circuits with this technology is a major challenge. More complex circuit structures are required to improve state-of-the-art performance in the deep-scaled 22 nm CMOS technology compared to other CMOS technologies with larger gate lengths. The third-order distortion cancellation concept was studied and extended with back-gate control, especially for the low-noise amplifier design in an FD-SOI CMOS technology. Based on the study, highly linear low-noise amplifiers are designed and implemented with the 22 nm FD-SOI CMOS technology. The high linearity ensures a high tolerance on the spillover from transmitter to receiver, making the proposed circuits more applicable to civilian automotive radar applications. The state-of-the-art input referred 1 dB compression point ($\mathrm{i}P_{1\mathrm{dB}}$) for low-noise amplifiers operating in the 77 GHz/79 GHz frequency band is improved to around −4 dBm by these works. To increase the linearity at the receiver side in a radar system, the passive ring structure was investigated to realize the frequency down-conversion mixer. The presented down-conversion mixer and low-noise amplifier are expanded into an in-phase and quadrature receiver. Experimental results showed very good performances with $\mathrm{i}P_{1\mathrm{dB}}$ around −9 dBm and double-sideband noise figure of 8 dB. For the circuit blocks at the transmitter side, a 79 GHz power amplifier is designed. The capacitive neutralization concept was studied and utilized in this power amplifier design to increase the gain and reverse isolation of the amplifier units. A binary-phase modulator is further integrated with the power

amplifier to enable binary-phase modulation for radar applications. This design is the first reported proof-of-concept design of a binary phase modulated transmitter in a 22 nm technology. It showed a very balanced performance and achieved the highest figure of merit defined by the International Technology Roadmap for Semiconductors at the time of the work.

Besides the study of circuit blocks operating in the 77 GHz/79 GHz band, power amplifiers are investigated for the ISM 24 GHz frequency band radars. For the broadband radar applications in this frequency band, a distributed power amplifier circuitry is investigated, which is well-known for the bandwidth but with low efficiency. The design concept for a distributed power amplifier is extended by this work. Supported by theoretical analysis, the number of stages and forward gain of the distributed power amplifier can be optimized, which in turn improves the efficiency of the whole circuit. To prove the concept, the distributed power amplifiers were implemented in a 130 nm SiGe technology. The designed circuits improved the state-of-the-art regarding output power and gain for the silicon-based designs with comparable efficiency at that time. It is worth noting that with integrated dc feedlines, no external bias-tee is required for the designed distributed power amplifiers, which strongly increases the integration ability. The presented distributed power amplifiers have been successfully implemented in several systems.

Kurzfassung

Die zivile Kfz-Radartechnik ist ein spannendes Thema angesichts der wachsenden Nachfrage nach sicherem Fahren und der Erforschung von Technologien für autonomes Fahren. Der Bedarf an leistungsfähigeren Radargeräten treibt die Millimeterwellen Radarforschung stark voran, insbesondere in Bezug auf wichtige integrierte Millimeterwellen Schaltungen. Diese Arbeit konzentriert sich auf die Analyse und den Entwurf integrierter Schaltungen für zivile Kfz-Radaranwendungen.

Um die Machbarkeit der Millimeterwellen-Schaltkreise für zivilen Kfz-Radar im 77 GHz/79 GHz Frequenzband zu untersuchen, wurden Chips in einer 22 nm FD-SOI CMOS Technologie implementiert. Die Realisierung von Millimeterwellenschaltungen mit dieser Technologie ist immer noch eine große Herausforderung. Es sind komplexere Schaltungsstrukturen erforderlich, um die Leistung in der tief skalierten 22 nm CMOS Technologie im Vergleich zu anderen CMOS Technologien mit größeren Gate-Längen zu verbessern. Das Konzept der Verzerrungsunterdrückung dritter Ordnung wurde untersucht und um eine Back-Gate-Steuerung erweitert, insbesondere für das Design eines rauscharmen Verstärkers in einer FD-SOI CMOS Technologie. Auf der Grundlage der Studie wurden hochlineare rauscharme Verstärker entworfen und mit der 22 nm FD-SOI CMOS Technologie implementiert. Die hohe Linearität gewährleistet eine hohe Toleranz gegenüber dem Übersprechen vom Sender zum Empfänger, wodurch die vorgeschlagenen Schaltungen besser für zivile Kfz-Radaranwendungen geeignet sind. Der auf dem neuesten Stand der Technik befindliche eingangsbezogene 1 dB Kompressionspunkt (i$P_{1\mathrm{dB}}$) für rauscharme Verstärker, die im Frequenzband 77 GHz/79 GHz arbeiten, wird durch diese Arbeiten auf etwa -4 dBm verbessert. Um die Linearität auf der Empfängerseite in einem Radarsystem zu erhöhen, wurde die passive Ringstruktur zur Realisierung des Frequenzabwärtsmischers untersucht. Der vorgestellte Abwärtswandlungsmischer und der rauscharme Verstärker werden zu einem In-Phase und Quadratur Empfänger erweitert. Experimentelle Ergebnisse zeigten sehr gute Leistungen mit i$P_{1\mathrm{dB}}$ um -9 dBm und Zweiseitenband-Rauschzahl von 8 dB.

Für die Schaltungsblöcke auf der Senderseite wurde ein Leistungsverstärker mit einer Zentralfrequenz von 79 GHz entworfen. Das Konzept der kapazitiven Neutralisierung wurde untersucht und in diesem Leistungsverstärkerentwurf verwendet, um die Verstärkung und die Rückwärtsisolierung der Verstärkereinheiten zu erhöhen. Ein binärphasiger Modulator ist außerdem in den Leistungsverstärker integriert, um eine binärphasige Modulation für Radaranwendungen zu ermöglichen. Dieser Entwurf ist der erste gemeldete Machbarkeitstudie eines binärphasenmodulierten Senders in einer 22 nm Technologie. Er zeigte eine sehr ausgewogene Performanz und erreichte die höchste Leistungskennzahl, die zum Zeitpunkt der Arbeit in der International Technology Roadmap for Semiconductors festgelegt war.

Neben der Untersuchung von Schaltungsblöcken, die im 77 GHz/79 GHz Band arbeiten, wurden Leistungsverstärker für das ISM 24 GHz Frequenzband Radar erforscht. Für die breitbandigen Radaranwendungen in diesem Frequenzband werden verteilte Leistungsverstärkerschaltungen untersucht, die zwar für ihre Bandbreite bekannt sind, aber einen geringen Wirkungsgrad haben. Das Designkonzept für einen verteilten Leistungsverstärker wird in dieser Arbeit erweitert. Unterstützt durch theoretische Analysen können die Anzahl der Stufen und die Vorwärtsverstärkung des verteilten Leistungsverstärkers optimiert werden, was wiederum die Effizienz der gesamten Schaltung verbessert. Um die Machbarkeit der Konzepte zu zeigen, wurden verteilte Leistungsverstärker in einer 130 nm SiGe Technologie implementiert. Die entworfenen Schaltungen verbesserten den Stand der Technik in Bezug auf Ausgangsleistung und Verstärkung für die Silizium-basierten Designs mit vergleichbarer Effizienz zu dieser Zeit. Es ist erwähnenswert, dass mit integrierten Gleichstromleitungen keine externen Netzwerke (Bias-Tee) zur Zuführung des dc-Stromes für die entworfenen verteilten Leistungsverstärker erforderlich ist, was die Integrationsfähigkeit stark erhöht. Die vorgestellten verteilten Leistungsverstärker wurden bereits erfolgreich in mehreren Systemen eingesetzt.

Original Publications

This dissertation is based on previous published works by this author. All the in IEEE published papers have been referenced in accordance to the IEEE copyright policy and are included in the list of publications at the end of this dissertation (List of Own Publications). Any tables or figures used from previously published documents with minor or no modifications are marked using the notation: [reference]©YYYY, Publisher. Additionally, footnotes are used at the beginning of the related chapters and sections to clarify the reuse of the corresponding materials.

Contents

1 Introduction

1.1 Motivation

The increasing demand for advanced safety features and the growing interest in autonomous driving have driven the evolution of radar systems for civilian vehicles and motivated the study and research of the related radar technologies. The history of radar can be tracked back to the experiments by Heinrich Hertz in 1886 that showed that radio waves were reflected by metallic objects. Based on this discovery, in the early 20th century German inventor Christian Hülsmeyer developed the device "telemobiloscope", which is a ship detection device intended to help avoid collisions in dense fog and can be recognized as the first device using radio waves to detect distant objects. The name "radar" came firstly in 1940 as an acronym for *radio detection and ranging*. For the civilian automotive radars the first investigations came up in the 1960s, and were carried out in the 1970s by Bendix, Info Systems Inc, RCA and General Motors in US, then followed by the Japanese companies Mitsubishi and Nissan [WHM21]. In Germany, AEG-Telefunken (Ulm, Germany) together with Bosch (Stuttgart, Germany) started researching radar technology for civilian automotive collision avoidance systems in 1973, realizing and testing a non-coherent pulsed radar prototype operating at 35 GHz [Wen98]. The first commercial 76 GHz automotive radar for passenger cars was introduced by Mercedes Benz in 1998/99. The system was built by Macom in US [Mei14, GJB+01]. After that more and more new generation radar sensors have been introduced for civilian automotive applications. Since 2010, the advanced driver assistance system (ADAS) has become a trend in the automotive market. Radar systems began to be migrated from high class cars to middle-end vehicles. Active safety systems such as automated emergency braking (AEB) are gradually becoming mandatory for new car assessment program. It is proven to improve safety and prevent accidents and fatalities. Almost every OFM uses at least one front-radar in its AEB system [NXP]. Since 2020, the introduction of artificial intelligence and autonomous driving becomes a key research topic of automotive radar. The resulting demand for higher performance and more integrated functions in such radars motivates significantly further research and study.

As the core of radar systems, integrated circuit (IC) technology enables the transmission, reception and processing of the corresponding radar signals, playing a key role in the implementation of the systems. Therefore the evolution of radar are always strongly associated with the development of semiconductor technology. From the standalone GUNN elements and Schottky diodes at the beginning to the gallium arsenide (GaAs) discrete or IC in the first millimeter-wave (mmW) radar sensors, the early research were based on the available technologies and devices at that time. As the development of silicon-based Silicon Germanium (SiGe) technology, it became more competitive due to the lower cost, higher integration densities and comparable speed. Starting in 2010 the market transitioned to silicon [WHM21]. As already proven in the mobile phone development, the next apparently inevitable technology transition is to complementary metal oxide semiconductor (CMOS). It provides further higher ability to fully integrated analog and digital devices, making single-chip solutions available. To further increase the integration level and reduce the system costs, there is more and more research interest in implementation of radar systems in deeply-scaled CMOS processes [LBE18]. This of course poses new challenges for mmW front-end circuit design.

This thesis presents a study on circuitry concepts and structures. The designs of some key circuit components for radar systems operating in the Industrial-, Scientific- or Medical (ISM) 24 GHz band and the 77/79 GHz band are proposed, which cover the main frequency range of current interest for civilian automotive radar applications. To verify the circuitry concepts, these designs are implemented in a 22 nm fully depleted silicon on insulator (FD-SOI) CMOS technology or a 130 nm SiGe technology, which are very advanced at the beginning of this work.

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1.2 Outline

The focus of this thesis is on the research of circuit design for civilian radars. Complete discussion about radar algorithms or application scenarios is not intended. The corresponding introduction is only to the extent necessary for overall understanding.

The thesis is structured in the following way. After the introduction about the motivation of this work in this chapter, the fundamental theories and general system structure about the nowadays commonly used frequency-modulated continuous wave (FMCW) radar are introduced in chapter 2.

The circuit design and characterization is detailed in chapter 3. It includes the design of low noise amplifier (LNA)s, down-conversion mixer, and power amplifier (PA) in the 77 GHz frequency band and the design of broadband PAs in the ISM 24 GHz frequency band. In the corresponding section, the circuit design principle is systematically represented. The proof-of-concept circuits are implemented and characterized through the laboratory experiments, and the measurement results are shown in the corresponding sections as well. The results are then compared with state-of-the-art.

At the end, the thesis is concluded with chapter 4 by a summary and an outlook for further improvement of the circuit designs for civilian automotive radar applications.