Beiträge aus der Elektrotechnik

Xin Xu

Analysis and Design of Millimeter-Wave Integrated Circuits for Wireless Communications in K/Ka/V Bands

VOGT

Dresden 2024

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., 2024

Die vorliegende Arbeit stimmt mit dem Original der Dissertation „Analysis and Design of Millimeter-Wave Integrated Circuits for Wireless Communications in K/Ka/V Bands“ von Xin Xu überein.

Gesetzt vom Autor

ISBN 978-3-95947-073-5

Jörg Vogt Verlag
Niederwaldstr. 36
01277 Dresden
Germany

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

Technische Universität Dresden

Analysis and Design of Millimeter-Wave Integrated Circuits for Wireless Communications in K/Ka/V Bands

Dipl.-Ing.

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der Fakultät Elektrotechnik und Informationstechnik

der Technischen Universität Dresden

zur Erlangung des akademischen Grades

Doktoringenieur

(Dr.-Ing.)

genehmigte Dissertation

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Tag der Einreichung:	27. February 2024
Tag der Verteidigung:	04. September 2024

Acknowledgment

I would like to thank everyone who has supported my work in the past few years. Special thanks go to Prof. Dr. Sc. techn. Frank Ellinger, who allowed me to work in his department in this field. His enthusiasm for high-frequency circuit designs and various suggestions for further research have inspired me extensively throughout my entire Ph.D. journey and will continue to encourage me for the rest of my life.

I extend my gratitude to Prof. Dr.-Ing. Corrado Carta and Dr.-Ing. Jens Wagner for the time they have always taken for extensive technical discussions and the critical review of my works. I would also like to express my thanks to Dr.-Ing. Stefan Schumann for his help in the measurements. Thanks to my colleagues who worked closely with me for their technical expertise and the friendly and open working atmosphere.

From the bottom of my heart, I thank my family, especially my wife - Yushu Xu - who has rejoiced with me in my successes and encouraged me in setbacks. Also, I would like to say to my lovely daughter, yet to be born: “Little girl, being your daddy is the greatest gift that I have ever been given!”

Peace of Mind, the Life is long.

Dresden, in December 2023 Xin Xu

Abstract

This thesis presents the analysis and design of different circuit concepts for the upcoming 5G and 60 GHz wireless communications with frequencies ranging from 24 GHz to 70 GHz in K/Ka/V bands. To prove the concepts, the involved circuits are implemented in the 22 nm Globalfoundries 22FDX® fully-depleted silicon-on-insulator (FD-SOI) complementary metal-oxide-semiconductor (CMOS) technology. This technology provides CMOS transistors specially optimized for high-frequency operations. Furthermore, choosing CMOS technologies allows the co-integration of high-performance digital circuits with millimeter-wave (mmW) circuit blocks, which benefits the cost, performance, robustness and compactness of the circuits. The circuits investigated in this thesis are designed for direct-conversion scenarios.

For 60 GHz applications, a comprehensive set of active and passive circuits intended to be integrated into a 60 GHz I-Q system has been analyzed and designed in this thesis. The main research interest here consists in designing switchable circuits, which can be set to low-power standby mode at idle time to save energy. To accomplish the switching function, different switching methods have been discussed in this work. A transistor back-gate based switching method has been proposed to overcome the drawbacks associated with the conventional front-gate based switching. It was the first time that transistor back-gates were utilized for the switching task of mmW circuits. All the active circuits designed in this thesis have successfully demonstrated the back-gate capability in terms of switching by the measurements. The designed two-stage power amplifier exhibits a gain of 23.3 dB, a maximum output power of 13.6 dBm and a maximum power-added-efficiency (PAE) of 28.3%. Its performance surpasses the other designs reported in terms of linearity and power efficiency. The gain peaking technique is widely applied in broadband amplifier designs, and its working principle is already well-explained. However, the impact of impedance mismatches associated with the gain peaking on the noise performance should be analyzed for low noise amplifier (LNA) designs. A theoretical analysis of the impact of impedance mismatches on noise performance has been conducted in this work, which gives a deeper understanding of the relationship between impedance mismatches and noise performance. The outcomes of this theoretical analysis indicate that noise performance will not be strongly affected by the high losses caused

by impedance mismatches, which shows the feasibility of applying the gain peaking technique in broadband LNA designs. The presented 60 GHz LNA based on the gain peaking technique achieves a broad bandwidth of 18.5 GHz. Its measured minimum noise figure is 3.3 dB, a record value among the LNA designs in the 60 GHz band. Thanks to the on-chip local oscillator (LO) driver, the 60 GHz up-conversion and down-conversion mixers presented in this work require the lowest LO power for operation compared to other designs. Power combining/division and I-Q generation are crucial steps for I-Q transceiver systems. Two Wilkinson power combiners/dividers based on transmission lines and lumped elements have been designed and compared. The lumped element based version shows less area consumption but similar performance. For I-Q generation, a novel cross-coupled transformer-based quadrature-phase coupler has been analyzed and designed. The applied capacitive cross-coupling improves the coupler coupling coefficient, which is limited by the low magnetic coupling between the transformer windings.

The primary focus of designing 5G mmW circuits in this work is investigating the feasibility of dual-band operation in the two 5G mmW band-sets – 28 GHz and 38 GHz. Designing dual-band circuits capable of operating in these two band-sets could lower the required resources for fabrication and the complexity of 5G mmW systems. Two 5G dual-band designs have been investigated in this thesis, indicating the high potential of designing dual-band circuits operating in the 5G mmW band. The presented dual-band vector-sum phase shifter provides 360° of phase tuning and a gain of better than 5 dB in both 5G band-sets. A novel phase-compensated RC poly-phase-filter (PPF) has been implemented in this design. The introduced phase compensation technique reduces the effects of layout parasitics, which cause drifts in phase and amplitude responses of the RC PPF. The up-conversion mixer in this work shows its dual-band capability with competitive performance in terms of conversion gain, linearity and energy consumption. These designs are the first showcases investigating dual-band operation in the 5G mmW band.

Zusammenfassung

Diese Arbeit präsentiert die Analyse und das Design verschiedener Schaltungskonzepte für die zukünftige drahtlose 5G- und 60 GHz-Kommunikation bei Frequenzen von 24 GHz bis 70 GHz in K/Ka/V-Bändern. Zum konzeptionellen Beweis werden die Schaltungen in der 22 nm Globalfoundries 22FDX® FD-SOI CMOS-Technologie implementiert. Diese Technologie bietet CMOS-Transistoren, die speziell für die Hochfrequenzanwendungen optimiert sind. Darüber hinaus bietet die CMOS-Technologien die Möglichkeit, digitale Hochleistungs-schaltungen mit mmW-Schaltungsblöcken zu integrieren, was sich positiv auf Kosten, Leistung, Zuverlässigkeit und Dimension der Schaltungen auswirkt. Die in dieser Arbeit untersuchten Schaltungen sind für die direkte Frequenzumwandlung ausgelegt.

In dieser Arbeit wurden aktive und passive Schaltungen für 60 GHz-Anwendungen analysiert und entworfen, welche in einem I-Q-Transceiver integriert werden. Das Hauptaugenmerk lag darauf, energieeffiziente Schaltkreise zu entwerfen, die im Leerlauf in einen energiesparenden Standby-Modus geschaltet werden können. Dazu wurden verschiedene Methoden untersucht, um die Schaltfunktion zu realisieren. Ein Back-Gate-basiertes Schaltverfahren wurde vorgeschlagen, um die Nachteile des herkömmlichen Front-Gate-basierten Schaltverfahrens zu beseitigen. Zum ersten Mal wurde das Transistor Back-Gate zum Schalten von mmW-Schaltungen verwendet. Die in dieser Arbeit entworfenen aktiven Schaltungen konnten durch Messungen erfolgreich das Back-Gate-basierte Umschalten demonstrieren. Der entworfene zweistufige Leistungsverstärker weist eine Verstärkung von 23,3 dB, eine maximale Ausgangsleistung von 13,6 dBm und einen maximalen PAE von 28,3% auf. Im Vergleich zu anderen Designs übertrifft er diese in Bezug auf Linearität und Energieeffizienz. Die Gain-Peaking-Technik ist eine bewährte Methode bei Breitbandverstärkern und wurde bereits in der Literatur ausführlich analysiert. Jedoch kommt es durch diese Methode zu Impedanzfehlanpassungen. Die Auswirkungen von Impedanzfehlanpassungen auf das Rauschverhalten von rauscharmen Verstärkern (LNAs) sollten berücksichtigt werden. Eine theoretische Analyse der Auswirkungen von Impedanzfehlanpassungen auf das Rauschverhalten wurde in dieser Arbeit durchgeführt, um ein tieferes Verständnis der Beziehung zwischen Impedanzfehlanpassungen und Rauschverhalten zu erlangen. Die Ergebnisse dieser theoretischen Analyse zeigen,

dass das Rauschverhalten durch die hohen Verluste wegen den Impedanzfehlanpassungen nicht stark beeinträchtigt wird. Dies zeigt das enorme Potenzial der Gain-Peaking-Technik für breitbandige LNA-Designs. Der vorgestellte 60 GHz LNA, bei dem die Gain-Peaking-Technik zum Einsatz kommt, erreicht eine hohe Bandbreite von 18,5 GHz. Die gemessene minimale Rauschzahl beträgt 3,3 dB, was ein Rekordwert unter den LNA-Designs im 60 GHz-Band darstellt. Dank des vollintegrierten LO-Treibers benötigen die in dieser Arbeit vorgestellten 60 GHz Aufwärts- und Abwärtsmischer im Vergleich zu anderen Designs die geringste LO-Leistung. Leistungskombination/-teilung und I-Q-Erzeugung sind entscheidende Schritte für I-Q-Transceiver-Systeme. Es wurden zwei Wilkinson-Leistungskombinierer/-teiler auf der Basis von Transmissionlines und diskreten Elementen entworfen und verglichen. Bei vergleichbarer Performance hat die Version, welche auf diskreten Elementen basiert, einen geringeren Flächenverbrauch. Für die I-Q-Erzeugung wurde ein neuartiger kreuzgekoppelter Transformator-basierter Quadratur-Phasen-Koppler analysiert und entworfen. Die angewandte kapazitive Kreuzkopplung verbessert den Kopplungskoeffizienten des Kopplers, der durch die geringe magnetische Kopplung zwischen den Transformatorwicklungen begrenzt ist.

Der Schwerpunkt beim Entwurf von 5G-mmW-Schaltungen in dieser Arbeit ist die Untersuchung der Machbarkeit des Dualbandbetriebs in den beiden 5G-mmW-Bändern – 28 GHz und 38 GHz. Der Entwurf von Dual-Band-Schaltungen, die in diesen beiden Bändern arbeiten können, könnte die nötigen Ressourcen für die Herstellung und die Komplexität von 5G-mmW-Systemen verringern. In dieser Arbeit werden zwei 5G-Dual-Band-Schaltungen untersucht, die das große Potenzial des Entwurfs von Dual-Band-Schaltungen für die 5G mmW-Bänder aufzeigen. Der vorgestellte Dual-Band-Vektor-Sum-Phasenschieber bietet eine Phasenverschiebung von 360° und eine Verstärkung von mehr als 5 dB in beiden 5G-Bändern. In diesem Entwurf wurde ein neuartiger phasenkompensierter RC-Polyphasenfilter implementiert. Die eingeführte Phasenkompensationstechnik reduziert die Auswirkungen parasitärer Effekte durch das Layout, welche Abweichungen im Phasen- und Amplitudenverhalten des RC-Polyphasenfilters verursachen. Der in dieser Arbeit vorgestellte Dual-Band-Aufwärtsmischer ist im Bezug auf Leistung, Mischgewinn, Linearität und Energieverbrauch auf dem Stand der Technik. Diese Entwürfe sind die ersten, die den Dual-Band-Betrieb in den 5G-mmW-Bändern untersuchen.

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1 Introduction

1.1 Motivation

The history of communication technologies is a human story of innovation and technological progresses. In the early days, humans relied on grunts, gestures, symbols, and so on to exchange information. Over time, the invention of the telegraph in the 19th century [1] marked an important turning point in the history of communication, enabling the first fast transmission of information over long distances. This was followed by the telephone, which further shaped the way of communication in human history and made real-time, long-distance communication possible.

Moving into the 20th century, radio communication gained momentum and spread widely throughout the entire world. Especially, the invention of mobile phones later on opened the door to massive commercial wireless communication, greatly expanding the scope and speed of information exchange. Mobile networks or cellular networks have come a long way, seeking higher data rates in the past decades. The first generation mobile network known as 1G, introduced in the early 1980s, was based on analog communication technologies, which only supports 2.4 Kb/s of data speed [2]. The 2nd generation of mobile networks, first launched in 1989, could serve up to around 10 Kb/s of date rate [3]. As time moved on to the 21st century, the 3G and 4G mobile networks pushed the speed to its new level of 1 Gb/s [4]. In the meantime, the wireless local area network (WLAN) standards 802.11a/b/g offering up to 54 Mb/s of date rate were launched due to the rapidly increased demand for wireless access of local networks [5]. The latest 802.11ax standard even supports 10 Gb/s wireless link [3]. Fig. 1.1 shows the data rates and maximal bandwidths of different wireless standards involving WLAN and cellular devices. Throughout the road map of wireless communication standards, a clear trend can be seen that the data rates were directly improved by increasing the communication bandwidth. Besides this, increasing the spectral efficiency with the help of advanced modulation method [6] is another way to achieve high data rates. This corresponds to the vertical growth between standards using the same bandwidth in Fig. 1.1.

The increasing demand for high-speed data transmission has constantly driven the development of wireless networks in the past decades and will

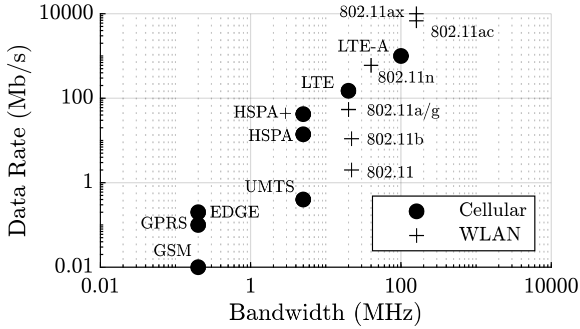

Figure 1.1: Data rates and maximal bandwidths of different cellular and WLAN standards [6, 7].

continue pushing the speed of those networks to higher levels. The ongoing Industry 4.0, Internet of Things and autonomous driving are creating countless application scenarios requiring higher data rates. This has posed significant challenges to existing wireless communication systems. Due to the depletion of spectrum resources in the lower frequency bands, moving to higher frequencies is a trend to satisfy the high requirement of high data rates of wireless systems in the near future. The new generation of wireless networks like the 5G mobile networks and the WLAN standard 802.11ay is expected to fulfill the challenging requirements by leveraging the high operating frequencies at millimeter-wave (mmW) range. The mmW frequency ranges from 30 GHz up to 300 GHz [8]. Due to the high spectrum resources available in mmW bands, systems operating in those bands can offer significantly higher bandwidth for data transmission compared to the conventional ones operating in lower frequency bands. The 5G mobile networks involve the mmW frequency bands around 28 GHz and 38 GHz [9], and could deliver a theoretical data rate of up to 20 Gb/s [8]. The 802.11ay standard using the 60 GHz frequency band has six channels with 2.16 GHz bandwidth of each, which enables a high communication speed of up to 100 Gb/s by applying channel bonding and aggregation [10].

All mentioned above forms the initial motivation of this Ph.D. project, where investigation and design of circuits for mmW wireless communications ranging from 24 GHz to 70 GHz is the central point. As it moves to higher frequencies, the circuits become power-hungry. Energy efficiency has become a central concern not only because of energy consumption but also because of the associated heat dissipation problems. This translates to another focus of this Ph.D. thesis, where the design of different energy-efficient circuits at mmW frequencies is researched. Advanced complementary metal-oxide-semiconductor (CMOS) technologies for high-frequency designs are preferable due to the possibility of integrating high-performance digital circuits together with mmW circuits, which leads to lower cost, compacter size, and better robustness and performance. The 22 nm fully-depleted silicon-on-insulator (FD-SOI) CMOS technology provided by Globalfoundries has been used in this thesis to prove the design concepts experimentally.

1.2 Objective of the Work

This Ph.D. thesis is based on the research carried out within the project *6G-life* and the project *Important Projects of Common European Interest (IPCEI)*. The project *IPCEI* covers several research sectors within the microelectronics and communication technologies from materials and tools to the chip designs and manufacturing processes [11]. A part of this Ph.D. project was completed as research activities in the frame of the *IPCEI* subproject - *GlobalFoundries Dresden Module One* founded by the Federal Ministry for Economics and Energy and by the State of Saxony. The rest of this Ph.D. project was completed as research activities in the frame of the project *6G-life* supported by the Federal Ministry of Education and Research of Germany in the programme of “Souverän. Digital. Vernetzt.”.

The project *6G-life* focuses on different scopes from robotics, human-machine interaction and communication technologies to microelectronic chip designs. Designing circuits for a 60 GHz switchable mmW front-end is one of the work packages within the project *6G-life*. This forms one of the research objectives in this work, where the analysis and design of different switchable circuits operating in the license-free 60 GHz band should be conducted. As a special focus, the study of suitable switching methods for designing switchable circuits at 60 GHz should be carried out. The realization of the switching function could reduce the DC power of circuits operating at mmW frequencies, when the circuits are at their idle time.

The subproject *GlobalFoundries Dresden Module One* also covers diverse research fields like investigating advanced microelectronic circuits, modules and packaging techniques crossing the fields from automotive radars to high-speed communications. Among them, the investigations of mmW circuits suitable for the coming 5G wireless communications form another objective of this Ph.D. project. Since the released 5G mmW band consists of two subsets - 28 GHz and 38 GHz [9], the analysis and design of circuits capable of dual-band operation in these two 5G band-sets is an essential focus.

1.3 Structure of this Thesis

This thesis is composed of five chapters. At the beginning of this thesis, the introduction explains the motivation and objectives of this Ph.D. project.

In Chapter 2, some fundamentals closely related to the research topics are presented. Different semiconductor technologies are reviewed and compared. The reason for selecting the 22 nm Globalfoundries 22FDX® FD-SOI CMOS technology for the designs in this Ph.D. project is explained. In addition, an overview of on-chip transmission lines including the transmission line theory and the discussions of different on-chip transmission line concepts is provided. The comparison of different transmission line concepts leads to the decision of the transmission line type selected in this project. The selected transceiver architecture determines the design of different circuit blocks intended to be used in a transceiver system. Thus, different transceiver architectures are discussed and compared in this chapter, leading to the final selection of the direct-conversion architecture.

Chapter 3 describes the design of a set of circuits intended to be used in a 60 GHz I-Q transceiver system including the design of power amplifier (PA), low noise amplifier (LNA), up-conversion and down-conversion mixers, and some passive circuits such as power combiner/divider and I-Q generation circuit. The design of a two-stage switchable power amplifier operating in the 60 GHz band is shown at the beginning of this chapter. To save energy at the circuit idle time, switching capability, which can switch the circuits to low-power standby mode, should be realized not only for the presented power amplifier but also for other related active circuits in this work. Different switching methods are discussed and compared. The transistor back-gate based switching outperforms the front-gate based version because it could overcome problems like voltage breakdown, circuit stability and switching speed, and DC routing complexity related to the front-gate based switching. As the second, the design of a 60 GHz broadband LNA is provided. Based on the gain peaking or gain distribution technique, the LNA could achieve a measured bandwidth of 18.5 GHz. The transistor back-gate is used in the LNA design to accomplish switching and variable gain control at the same time. As next, the design of 60 GHz back-gate based switchable down-conversion and up-conversion mixers is shown. The down-conversion mixer is based on a differential pair for power saving, and the up-conversion mixer is based on the Gilbert cell. After the mixer design, two Wilkinson power combiners/dividers based on transmission lines and lumped elements are described. A comparison of them is conducted, which shows that the lumped element based version provides similar performance but consumes significantly less area. At the end of this chapter, a cross-coupled 60 GHz transformer-based quadrature-phase coupler is investigated.

Chapter 4 presents two dual-band designs for 5G mmW applications. At first, a 5G dual-band mmW phase shifter is designed and characterized. The phase shifter is based on the vector-sum principle relying on I-Q vector synthesis. To achieve a compact chip size, a poly-phase-filter is used to generate the required quadrature-phase vectors. To overcome the degradation of the quadrature phase due to parasitics in the layout, an advanced phase compensation technique based on parallel capacitive feedback is introduced. In addition, a 5G dual-band up-conversion mixer is presented in this chapter. The mixer core is based on the Gilbert cell to guarantee a high LO suppression. An additional common-mode-rejection transistor is added at the bottom of the Gilbert cell to suppress the common-mode LO further.

Chapter 5 gives a conclusion of this work and an outlook on possible works to be carried out in the future.