Chapter 1

Introduction

The millimeter-wave (mm-wave) region of the electromagnetic spectrum covers the range of wavelengths from one centimeter to one millimeter. It corresponds to radio band frequencies of 30 GigaHertz (GHz) to 300 GHz (by extension, 24 GHz is also often considered as part of the mm-wave domain). The high frequency of mm-waves as well as their propagation characteristics make them a real asset for a variety of applications including high-data-rate wireless communication systems [1], and Radio Detection and Ranging (radar) [2].

An essential advantage of mm-waves is the possibility to transmit large amount of informations with a small ratio $\frac{BW}{f_o}$ (where BW is the assigned bandwidth of the application and f_o its center frequency). Therefore consumer electronics in the mm-wave domain will allow in the future the transmission of e.g. video data suitable for high-definition television (HDTV) [3].

Radar sensors take advantage of the mm-waves. Due to the shorter wavelength, significantly smaller antenna dimensions are required in e.g. a collision-avoidance automotive radar, which might lead in the future to fully integrated systems including on-chip antenna [4].

The mm-wave domain presents a large spread in atmospheric attenuation. A wide spectral window centered around 35 GHz allows the realization of long range communication systems. At 60 GHz, the oxygen molecules will interact with the electromagnetic radiation and absorb a large amount of energy. This means that while 60 GHz is not a good frequency for long-range radar or long-range communication systems, it is perfectly suitable for short-range communications, such as local wireless area networks used for portable computers [5]. Another possible application operating at 60 GHz is a communication system between satellites in high earth orbit.

Another benefit of mm-waves is the low amount of currently existing applications, which drastically reduces the chances of interference.

Now that various advantages of mm-waves have been highlighted, the question of suitable technologies remains.

In the late 1980s, Silicon (Si) bipolar technologies reached their limit with transit frequencies (f_T) around 30 GHz. At that time, the compound semiconductor industry was leading the market of applications operating in the millimeter-wave domain. In the early 1990s, the first SiGe heterojunction bipolar transistors (HBTs) came out of the research laboratories and entered production [6–8]. Since then, the technologies have improved and reached outstanding speed performance with f_T far above 300 GHz and even 500 GHz under certain conditions [9]. These advances toward higher speed make SiGe HBTs one of the greatest competitor of III-V compound semiconductor devices such as High Electron Mobility Transistors (HEMTs) in area such as optical fiber transmission systems, high data-rate wireless communications, and radar. While III-V compound semiconductors suffer from major issues such as high cost, low integration density and even yield problems for advanced technologies, SiGe bipolar technologies overcome all these problems [10].

Unfortunately, SiGe bipolar devices require a large amount of masks during fabrication process which leads to high cost if a low amount of integrated circuits (ICs) is required. This aspect is progressively worsened because of complex devices containing features that allow to improve their speed and to decrease critical parasitics (such as e.g. substrate coupling using deep trench isolation). Another critical issue of very high-speed SiGe HBTs is their low breakdown voltage, which inevitably leads to a lower power capability for transmitters. As a rule of thumb, battery based applications (such as mobile phone) should use technologies with an f_T at least ten times higher than the f_{op} (where f_{op} is the operational frequency of the application) and applications which are not using batteries should be designed with technologies with an f_T of at least three times the f_{op}. However, using specific topologies, these barriers can be broken, thus leading to a drastic cost reduction. Circuit topologies which are capable of achieving such performance are emphasized in this work. These ICs were developed through several projects and therefore operate at different frequencies. But more importantly, all these ICs achieved a high f_{op}/f_T ratio.

In order to significantly decrease the cost of an IC, special emphasis can be placed on design re-use and reconfigurability. The layout of an IC can be designed in a way that easy modifications can be made in future designs. In this way, once a design has been successful and the accuracy of its simulation has been demonstrated, it will be possible to use it as a foundation to develop other similar ICs operating at different frequencies. By reducing the amount of redesign steps and modified masks, drastic cost and time reduction can be achieved. This design aspect will be described as well.

Because the presented circuits were designed to be implemented in a super heterodyne receiver or in a short range automotive radar, the next chapter gives an overview of possible architectures. Then, the technologies used to design the ICs will be presented. Afterward, because reactive elements with inductive behavior were realized using thin-film microstrip lines or on-chip spiral inductors, a chapter will be dedicated to these two elements and to their implementation in the simulation environment. Finally, the four main blocks of an RF front-end of a super heterodyne receiver and a short range automotive radar (amplifiers, VCOs, mixers, frequency dividers) will be described in details.

Chapter 2

Super Heterodyne Receiver and Automotive Radar

2.1 Introduction

As previously explained in Chapter 1, the developed ICs were realized for a wide range of applications which, however, can be narrowed down to two major system architectures: the superheterodyne receiver (SHR) and the frequency modulated continuous wave (FMCW) radar. In order to give a brief overview of the systems on which the circuits will be implemented in the future, a chapter is dedicated to these two approaches.

2.2 Super heterodyne receiver

The SHR [11] was invented by Armstrong and patented in 1918. In the SHR, a weak incoming RF signal at frequency f_{RF} is amplified using a LNA and then converted to a lower frequency (f_{IF}) using a local oscillator (LO) and a mixer. The signal with frequency f_{IF} is then demodulated to recover the initial data. A block diagram of a potential mm-wave SHR front-end is presented in Fig. 2.1. As can be seen, the receiver is fully differential. This is highly recommended for silicon based technologies in order to reduce the influence of packaging, which may be very critical and costly at this frequency range [12]. The advantages of such an approach are:

- On-chip noise generation is substantially reduced [13, 14]
- Clock generation in optical fiber systems is simplified due to the differential clock input of the driven circuits [15].

- Decoupling of supply and bias voltages is less critical due to the virtual ground nodes [16].
- Virtual ground nodes allow the realization of adjustable on-chip inductors (discussed in Chapter 5). Hence, the same IC can be used for different applications in a wide frequency range.

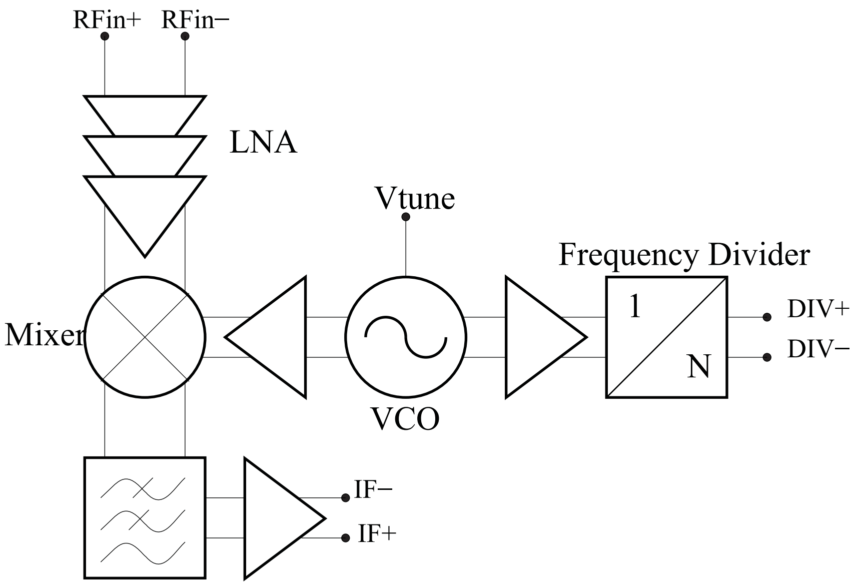

Fig. 2.1: Block diagram of a potential millimeter-wave SHR front-end

The use of a frequency divider is necessary to build a phase lock loop (PLL). This addition is not mandatory, however the implementation of a PLL leads to a drastic improvement of the oscillator phase noise as well as frequency stability and therefore to a higher overall performance of the SHR.

2.3 Short range and long range automotive radar

At the beginning of the third millennium, each year worldwide, over one million persons are killed in traffic and over 50 million are injured. In Germany alone, in 2001 over two million accidents resulting in almost 500 000 casualties occurred. The table 2.1 gives an overview of the accidents and the resulting casualties and deaths that occurred between 2001 and 2003 in Germany [17].
An important study was recently performed to try and understand the reasons of these traffic accidents worldwide [18]. The table 2.2 gives a very good insight to explain the great interest in automotive radar. As it can be seen, all accidents in categories marked

	2001	2002	2003
Number of vehicles	52 487 300	53 305 900	53 655 800
Number of accidents	2 373 556	2 289 474	2 259 567
Number of accidents with casualties	375 345	362 054	354 534
Number of casualties	494 775	476 413	462 170
Number of deaths	6 977	6 842	6 613

Tab. 2.1: Overview of the accidents occurring in Germany between 2001 and 2003

reason	percentage
Inattentiveness of the driver	68 % $\surd$
Driver driving too close from the front vehicle	9 % $\surd$
Driver driving too close from the front vehicle and inattentiveness	11 % $\surd$
Alcohol	9 %
Other	3 %

Tab. 2.2: Overview of the reasons resulting in car accidents

with a "$\surd$" could be avoided or at least drastically reduced by using radar sensors.
Research on automotive radar had already begun in the early 1970s [19]. However, such systems were only implemented e.g. in the class-S of Mercedes at the very end of the 20th century. In 1999 the first automotive long range radar (LRR) sensors operating at 76.5 GHz were introduced for adaptive cruise control (ACC). Furthermore in autumn 2005, the first cars equipped with 24 GHz short range radar (SRR) sensors in combination with a 76.5 GHz LRR sensor were brought onto the market enabling new safety and comfort functions such as e.g. stop-and-go operation, autonomous pre-safe braking, pre-crash warning, and parking assistance. Future advanced driver assistance functions are under way. In Europe, however, the 24 GHz ultra wideband (UWB) frequency band is only temporarily allowed until end of June 2013 with a maximum fleet penetration rate of 7% [20]. This limitation is due to the fact that the SRR radar is sharing the frequency band with other applications such as radioastronomy and this can lead to highly critical interference (the incoming signal in radioastronomy applications is always extremely weak). From the mid-2013 new cars will have to be equipped with SRR sensors operating in the frequency band from 77 GHz to 81 GHz [21].
The most adopted system architecture for SRR is the FMCW radar [22]. This is a system where a continuous wave radio energy with known stable frequency is modulated by a triangular modulation signal so that it varies gradually. This signal is then mixed with the signal reflected from a target to produce a beat signal. Variations of modulation are possible (sine, sawtooth, etc), but the triangle modulation is used in FMCW radars

where measurements of both range and velocity are desired, as in ACC systems. The beat signals are passed through an Analog to Digital Converter (ADC), and digital processing is performed on the result. FMCW radars can be built with one antenna using e.g a circulator. Many modern systems use separate transmitter and receiver antennas. Because the transmitter is on continuously at effectively the same frequency range as the receiver, special care must be exercised to avoid saturating the receiver stages. A block diagram of a potential 77-81 GHz SRR front-end architecture is presented in Fig. 2.2.

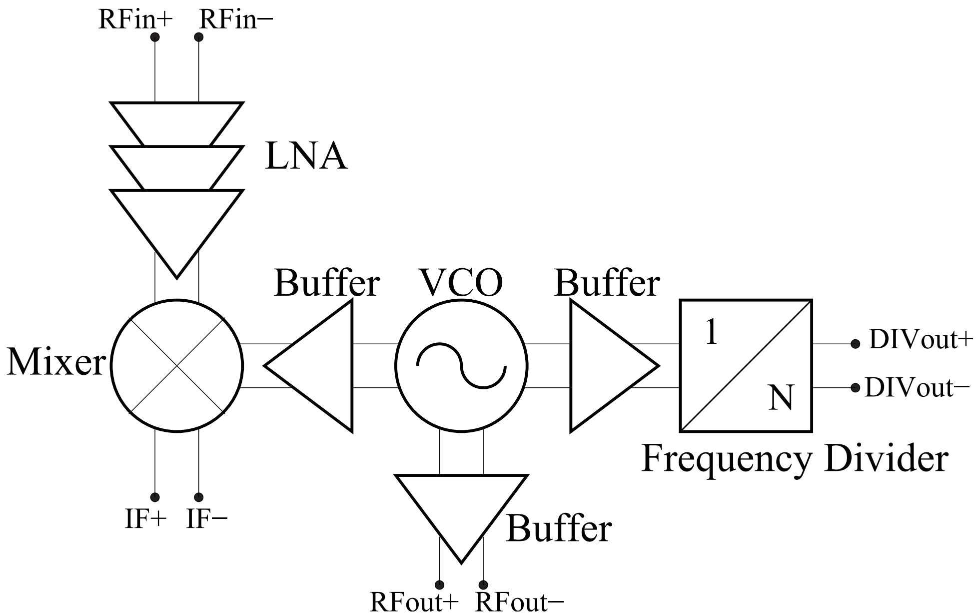

Fig. 2.2: Possible topology of a 77-81 GHz SRR front-end architecture

In this configuration, the VCO drives three output buffers which are connected to a frequency divider, the transmit antenna (RF_{out+} and RF_{out-}) and a down-converter mixer. The frequency divider is used to build a phase-locked loop (PLL) which is necessary to improve the phase noise of the VCO. As it can be seen, the topology of the whole FMCW radar is differential. The motivation for such approach was previously presented in Section 2.2.