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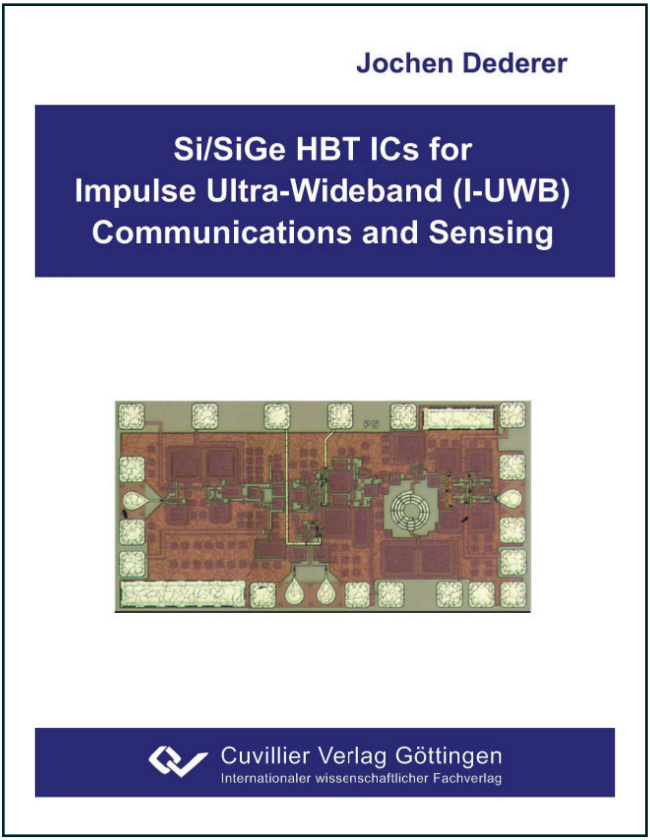
Si/SiGe HBT ICs for Impulse Ultra -Wideband (I -UWB) Communications and Sensing



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Chapter 1

Introduction

1.1 Motivation

Ultra-Wideband (UWB) is one of today's most fascinating technologies in the wireless world due to its unique features such as low radiated power spectral density, tremendous capacity potential, robust performance under multipath conditions, fine time resolution and the added benefit of potentially low cost hardware implementations. Hence, UWB has the potential to open up a new era in wireless transmission, although the underlying concept - namely spreading the radio signal energy over a very large bandwidth - is not in the least a new invention. In fact, already more than 100 years ago, the spark gap transmission designs of Marconi and Hertz essentially employed UWB signals which occupied an instantaneous bandwidth vastly exceeding the information rate. Pioneer work in transient analysis and time-domain measurements in the early 1960s and the patenting of "short-pulse" systems in the early 1970s were further landmarks in the history of UWB radio [1]. The early applications of UWB were primarily radar related because of the fine range resolution that comes with large bandwidth and the low probability of detection which is associated to the low radiated power spectral density. Seen from a communications perspective, it was not until the late 1990s that UWB experienced a breakthrough with the development of fundamental concepts of time-hopping impulse radio [2],[3]. A tremendous interest in commercialization of the UWB technology was triggered in 2002 when the Federal Communications Commission (FCC) issued its First Report and Order on UWB technology [4]. This release manifested a new approach in the regulation of RF emissions by allowing several gigahertz of spectrum, which has been originally allocated exclusively for narrowband applications, to be overlaid by UWB devices.

There are two common forms of UWB: one based on short duration pulses with several gigahertz of bandwidth and another using multiple frequency bands. The latter is primarily targeted for high data rate, short distance data communications. Within the context of high data rate, possible UWB application areas include internet access, multimedia services and wireless peripheral interfaces for cable replacement. The focus of this thesis is on short-pulse, carrier-free UWB which is generally referred to as impulse-UWB (I-UWB). I-UWB has the inherent advantage of low complexity, low cost transceiver topologies which arise from the carrier-free nature of the signal transmission. The low duty cycle of I-UWB pulses can minimize power demands by time gating of transceivers, thus enabling a large variety of long-life battery operated devices, e.g. for use in hazardous environments or areas which are difficult to access. The short duration pulses provide fine range resolution for distance measurements, allow the definition of precise range gates (e.g. for use in collision avoidance) and enable precise localization by combination of distance measurements from different sensor nodes. The capability to provide both location awareness and communications has made I-UWB an ideal candidate for location based services that emphasize low power consumption and precise location awareness instead of high data throughput. Seen from a regulatory perspective, low-rate I-UWB profits from extended range operation due to higher peak powers than those granted for high-rate applications [5]. Medical technology is another field where I-UWB can be used with great benefit [6]. First of all, the extremely low radiated power spectral density, and consequently low probability of interference to medical equipment, is a key requirement for use in clinical settings. Energy efficient operation is important for low data rate communication with implanted sensors or actuators, which require long-life battery operation. Moreover, due to the simple system architectures and the thereby achievable miniaturization of transceivers, the implantation of UWB sensors and actuators becomes minimally invasive. The high spatial resolution of I-UWB enables radar imaging with unattained precision - a feature which might be employed for tumour detection. Contact-less monitoring of respiration or heart beat motions is another very promising application since it obviates the need of electrodes as known from conventional techniques.

In summary, the thesis targets the development of innovative integrated circuits (ICs) for I-UWB systems with an inexpensive Si/SiGe heterojunction bipolar transistor (HBT) technology, thereby achieving significant improvements over earlier reported work in this area through

- inclusion of communications and sensing in one system concept
- excellent sensitivity and precision ranging
- low-complexity UWB transmitter and receiver architectures
- increased miniaturization and reduced cost of UWB transmitters and receivers with full monolithic integration as the ultimate goal.

1.2 Structure of the work

This thesis presents the design and evaluation of Silicon based I-UWB transmitter and receiver ICs with record performance characteristics. A block diagram of the realized I-UWB system is shown in Fig. 1.1. The transmitter (TX) consists of a pulse generator IC which is directly connected to a broadband antenna. The receiver (RX) comprises a broadband antenna and a fully monolithic correlation receiver IC which includes a low-noise amplifier, two single-ended to differential converters, an analog multiplier, a low-pass filter, a buffer amplifier and a template pulse generator for the correlation detection.

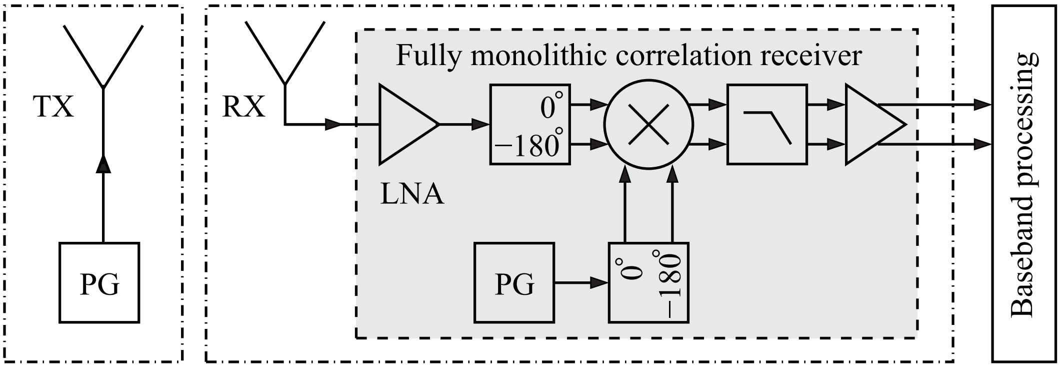

Figure 1.1: Block diagram of the realized I-UWB system with pulse generators (PG), antennas, low-noise amplifier (LNA), single-ended to differential converters, multiplier, low-pass filter and buffer amplifier.

The thesis is organized as follows. Chapter two gives a short overview about regulatory issues, relative merits of single-band I-UWB versus multi-band UWB and introduces the Si/SiGe process that has been utilized in the course of this work. Chapter three elaborates on possible pulse shapes for I-UWB transmission and focuses on the design of fully monolithic pulse generator ICs which resemble higher order derivatives of the Gaussian impulse. Chapter four includes a brief overview of I-UWB receiver design principles, describes three different design approaches of low-noise amplifiers and covers the realization of an analog correlator IC. Precise range measurements are demonstrated in chapter five. Chapter six presents the first reported 3.1-to-10.6 GHz I-UWB correlation receiver realized fully monolithically in a Si/SiGe HBT technology.

Chapter 2

UWB Design Considerations

This chapter deals with fundamental approaches of UWB operation which arise from the regulatory constraints for UWB transmission. Characteristics of multi-band as well as single-band UWB approaches are briefly discussed, showing both their distinct advantages and drawbacks either for communications, sensing, or - where applicable - the combination of both. The focus of the discussion is on performance characteristics in terms of achievable data rates, sensitivity, interference immunity and positioning accuracy balanced against associated hardware complexity. Finally, the utilized Si/SiGe HBT process is briefly introduced, highlighting its great potential for the commercialization of UWB devices.

2.1 Regulations

On February 14, 2002, after extensive commentary from industry, the Federal Communications Commission (FCC) issued a First Report and Order [4], which classified UWB operation into three categories:

- Communications and measurement systems
- Imaging systems, including ground penetrating radar, through-wall imaging, medical imaging and surveillance systems
- Vehicular radar systems.

Each category was regulated with specific emission limits in the form of spectral masks. This thesis has its focus on applications which occupy the 3.1-to-10.6 GHz frequency band. Maximum emissions are at an average effective isotropic radiated power (EIRP) density level of -41.25 dBm/MHz and a peak EIRP density level of 0 dBm in a 50 MHz bandwidth[1]. Considering the hypothetical case where a transmitter uses the entire band of 7.5 GHz of bandwidth, this implies a maximum average EIRP as low as 0.56 mW. Outside the 3.1-to-10.6 GHz frequency band, the radiated power spectral density has to be significantly decreased to avoid inadvertent jamming of existing systems such as Global Positioning System (GPS) receivers. According to the FCC's wording: for a radio device to be considered UWB, the 10-dB bandwidth ($f_H - f_L$) must be at least 500 MHz, and the fractional bandwidth $2(f_H - f_L)/(f_H + f_L)$ must be at least 0.2, as determined by the -10 dB power emission points f_H (designates the upper frequency band boundary) and f_L (designates the lower frequency band boundary). The FCC regulation does not require the exclusive use of short-pulse signals and does not force certain types of modulation. Thus, many possible modes of operation may be developed within these restrictions, which can be broadly grouped into single-band and multi-band UWB. Several solutions exist in between these approaches, e.g. a single-band may be notched into two sub-bands to avoid interference to and from colocated services. Moreover, the solutions may or may not utilize a carrier frequency, which makes the design space for UWB operation even more complex. In the following, prevalent UWB operations are grouped into multi-band approaches and single-band I-UWB.

2.1.1 Multi-band UWB

Generally, multi-band systems divide the allocated 3.1-to-10.6 GHz bandwidth in several sub-bands where each of these sub-bands has a minimum 10-dB bandwidth of 500 MHz to comply with FCC regulations. Splitting the UWB spectra into a number of sub-bands allows the use of a modified form of conventional modulation techniques like orthogonal frequency division multiplexing (OFDM) and code division multiple access (CDMA) within each sub-band. Early work on multi-band UWB systems employs multiple, consecutively sent narrowband pulses which occupy different frequency sub-bands, thus creating an effective broadband UWB pulse [8],[9]. This is typically accomplished by modulating appropriately shaped time-domain pulses with sinusoidal carriers which determine the center frequency of the corresponding spectral envelopes [10]. The dynamic ability of spectrum allocation is of advantage to meet regulatory constraints. Moreover, multi-band systems provide additional flexibility in dealing with a narrowband interferer (e.g. overlaid 802.11a wireless local area network (WLAN) systems which exhibit power levels several order of magnitude higher than the UWB emission limits) by possibly omitting frequency bands which suffer from strong interference. Consequently, this scheme is good for interference considerations but greatly increases system complexity due to the applied oscillators.

[1] The European Commission has issued licensing regulations for UWB in Europe with additional spectral restrictions [7]. Simular regulations are under consideration worldwide, albeit not always with the same generous spectral width as in the United States. The focus of this thesis is on UWB regulations in the United States.

Much effort has been invested in the multi-band orthogonal frequency division multiplexing (MB-OFDM) proposal which is, beside the competing direct sequence spread spectrum (DS-UWB) approach, a viable candidate for wireless personal area networks (WPANs). The MB-OFDM approach is a multi-carrier transmission system which divides the unlicensed 3.1-to-10.6 GHz spectrum into 528 MHz-wide sub-bands with 128 subcarrier tones [11]. Consecutive symbols are OFDM modulated over different sub-bands with a frequency hopping scheme. There are at least two key issues with this approach. First, the generation of OFDM symbols through digital signal processing requires the use of Inverse Fast Fourier Transform (IFFT) circuit blocks. Second, the frequency hopping approach requires complex frequency synthesizers which have to cover a wide frequency range and, based on proposed system requirements [12], also have to meet fast switching speeds in the order of a few nanoseconds. One option to achieve the required hop-times is to take dedicated phase-locked loops (PLLs) to generate each required local oscillator (LO) frequency independently and select one according to a band select command [13]. In terms of spurious performance this solution might be a good choice, but it comes at the cost of both a large occupied die area and a high power consumption. Other approaches comprise a single PLL and a number of single-sideband (SSB) mixers to generate different frequencies. The principal idea is to combine a fixed frequency with a variable low frequency [14], [15]. The required low frequencies are generated by dividing down from a common reference. The advantage here is a reduced hardware complexity. However, a common drawback of frequency synthesizers using dividers and SSB mixers are spurious components at the mixer outputs, e.g. unwanted spectral components due to harmonic distortions of the low frequency signals. The MB-OFDM receiver architecture is very similar to a conventional OFDM system, including local oscillators, mixers, analog-to-digital converters (ADCs), a gain control system to prevent ADC clipping and complex digital function blocks in the baseband processing as shown in Fig. 2.1 [16]. Despite its tremendous implementation complexity, the MB-OFDM approach has been, and still is, heavily promoted by industry. Reasons for the attracted attention include good coexistence with narrowband systems such as 802.11a, simple adaptation to different regulatory environments of various countries and future scalability by adding more bands. One might also argue that the MB-OFDM technique is the most mature approach as it applies rather conventional modulation strategies with transceiver architectures that are similar to traditional narrowband wireless transceivers. However, with MB-OFDM, the basic idea of cheap, low complexity, low power consumption UWB devices is lost which might explain why wide commercial use of MB-OFDM communication systems is still not in place.

A pulse-based proposal for high data rate UWB communications is a direct sequence (DS) technique which supports operation in two different bands: one band nominally occupying the spectrum from 3.1 to 4.9 GHz (the low band), and the second band nominally occupying the spectrum from 6.2 to 9.7 GHz (the high band), thus omitting the highly populated Unlicensed National Information Infrastructure (U-NII) frequency band [17]. DS-UWB achieves spreading gain by transmitting multiple pulses per bit. In case of the

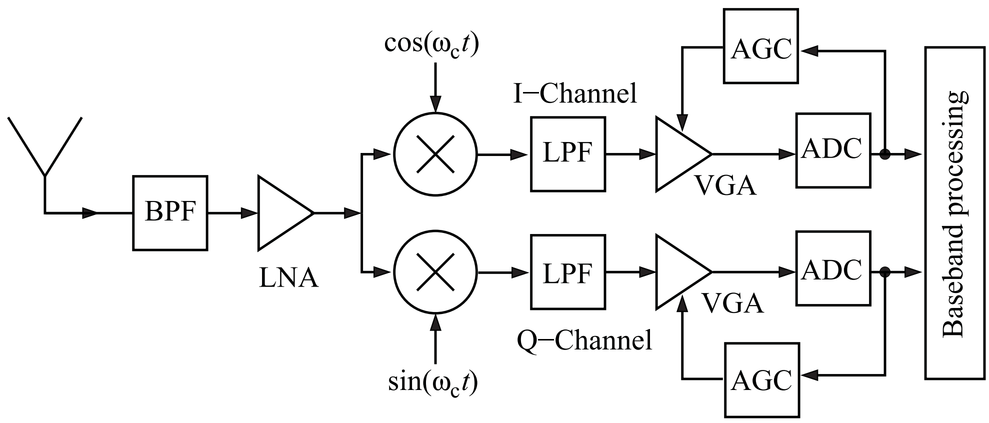

Figure 2.1: Simplified block diagram of MB-OFDM receiver architecture with band-pass (BPF) and low-pass filters (LPFs), LNA, local oscillators, mixers, analog-to-digital converters (ADCs), automatic gain control (AGCs) with variable gain amplifiers (VGAs) and digital function blocks in the baseband processing (frame detection and synchronization, FFT transformation, de-interleaving, Viterbi decoding and de-scrambling).

UWB Forum's proposal for the failed IEEE 802.15.3a standardization attempt, a wide bandwidth is achieved by modulating high rate wideband pulses on to a carrier. Proposed modulation schemes include bipolar phase shift keying (BPSK) and 4-ary biorthogonal keying (4-BOK). The amplitudes of the pulses are modulated by dedicated pseudo random spreading sequences for multiple access. The DS-UWB proposal is considered to be more flexible than the MB-OFDM approach as optional coding and modulation modes allow a trade-off between complexity and performance. Most importantly, the DS-UWB proposal shares the advantages of I-UWB systems which are associated with the wide occupied bandwidth of the single pulses. However, as with the MB-OFDM proposal, promoters of DS-UWB must face the question if there is a sufficient performance and cost advantage over conventional approaches which justifies the system complexity.

2.1.2 Single-band I-UWB

Considerable interest in UWB technology centers on carrier-free, single-band I-UWB approaches which involve the use of short duration, sub-nanosecond time-domain pulses. The corresponding frequency spectrum of the pulses occupies a fractional 10-dB bandwidth of up to 110 % or, equivalently, a 10-dB bandwidth of up to 7.5 GHz, to comply with FCC regulations. Advantages of broadband I-UWB over multi-band alternatives include the ability to finely resolve individual multipath components at the receiver and the rejection of multipath cancellation effects since the short pulse duration prevents significant time-domain overlap of the pulses. It is important to note that the received time-domain waveforms of each distinct path can show little resemblance to the received waveform of the line-of-sight path as they have undergone distortions due to reflections, scattering or diffraction [18]-[20]. On the one hand, the high sensitivity to different scatterers makes I-UWB approaches particularly well suited for radar and sensing applications, but on the other hand it makes it difficult for communication receivers to fully exploit the multipath diversity [21]. In communications, the multipath richness can be exploited with multi-finger Rake receivers, though this is achieved at the expense of increasing the receiver complexity. From a radar and sensing perspective, the large instantaneous bandwidth and short pulse duration identifies more target information such as material or shape and improved range accuracy[2] [17].

In case of data transmission, the choice of modulation is driven by the trade-off between data rate and link distance and, equally important, by the necessary hardware complexity of the transmitter and receiver architectures, respectively. Within the context of simple transceiver architectures, modulation schemes based on pulse position modulation (PPM), possibly combined with time-hopping for spreading the spectrum to minimize effects of spectral lines, and simple on-off keying (OOK) modulation, are of particular interest. Changes in data rate and transmission range can be accomplished by changing the pulse repetition frequency in combination with adjusting the rate of pulses per data symbol. In the course of this work, modulations schemes based on OOK are implemented as described in more detail in chapter 6.

In summary, the targeted inclusion of communications and sensing in one common RF platform favors single-band I-UWB against multi-band approaches. It has to be pointed out that the large occupied bandwidth also accounts for the design challenges observed in I-UWB systems: Single-band I-UWB systems must coexist with other systems which dictate the linearity requirements of the RF frontend and necessitate additional receiver complexity as described in chapter 4. Precise synchronization is another major issue. Finally, the circuit design of the RF frontend (low-noise amplifiers, correlators, pulse generators, etc.) faces the difficulty to cover an extremely large fractional bandwith.

2.2 Technology

Already more than ten years ago, Si/SiGe HBT transistors with high Germanium content in the base were capable to achieve excellent noise performance (noise figures below 1 dB at X-band frequencies) and high intrinsic transistor speeds (current gain cutoff frequencies exceeding 100 GHz) at relaxed lateral scaling from todays point of view without sub-micrometer lithography [24]. These performance characteristics are already sufficient for adequate UWB circuit design. This observation puts the ongoing debate, whether CMOS or bipolar technologies are the most advantage path to UWB commercialization, in a different light. First, the claimed cost advantage of CMOS is, at best, only true

[2]For a more in-depth discussion of relative merits of I-UWB radars versus narrowband radars, the reader is referred to some of the excellent literature on this topic, e.g. [22],[23].

for high volume production. This is due to the fact that microwave CMOS technologies require an aggressive lateral scaling with consequently high mask costs. A benefit which is often claimed with CMOS is its low power consumption. However, at microwave frequencies, this is not generally true. Finally, fast time-to-market requires well established technologies with mature device modeling, offering a higher possibility of first pass success and higher yields, respectively. In summary, conservative, well established Si/SiGe HBT processes are excellent candidates for the first phase of UWB commercialization.

Si/SiGe HBTs

In general, operation of bipolar transistors at microwave frequencies requires a short base transit time to achieve a high transit frequency (current gain cutoff frequency f_{T}) and thus an adequate intrinsic speed. Low-noise performance requires the combination of a low base resistance and a high current gain, where the latter has to be maintained at low collector currents necessary for low noise operation [24]. From a technological perspective, these characteristics require a thin, highly doped base layer with a correspondingly short transit time and a low base sheet resistance. The property of SiGe alloys which is of interest in that context is the bandgap energy which is smaller than that of Silicon. The difference in bandgap energy allows for the realization of hetero-interfaces where the majority of the band offset occurs in the valence band, thus forming a high potential barrier for unwanted injection of holes from the base into the emitter while the wanted injection of electrons from the emitter into the base is hardly affected. Compared to homojunction transistors, the latter leads to a potential current gain enhancement. In technical realizations, the current gain enhancement is traded for a dramatic increase in base doping and a simultaneous decrease in emitter doping [25]. The first allows low base resistances at thin base layers while the second counteracts tunneling breakdown of the base-emitter diode. All ICs described in this thesis were realized in the commercially available Telefunken Semiconductors (formerly ATMEL) Si/SiGe HBT foundry process with minimum $0.8\,\mu$m drawn feature size (effective emitter width $0.5\,\mu$m) [26]. Using a selective collector implant, high speed (f_{T} =80 GHz, collector-emitter breakdown voltage $BV_{\mathrm{CEO}} = 2.4\,\mathrm{V}$) and high breakdown voltage ($BV_{\mathrm{CEO}} = 4.3\,\mathrm{V}$, $f_{\mathrm{T}} = 50\,\mathrm{GHz}$) transistors can be combined in a single chip. The process offers three aluminum metalization layers, four different types of resistors and dielectric MIM capacitors as well as nitride capacitors. SiO_2 is used to isolate the metalization layers. Two types of substrates, high resistance $1000\,\Omega$cm and conventional $20\,\Omega$cm Silicon p-type substrates are available. Throughout the thesis, all presented monolithic microwave integrated circuits (MMICs) were realized on conventional $20\,\Omega$cm substrates.