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Si/SiGe Integrated Circuits for Impulse-Radio UWB Sensing and Communications

(Invited Paper)

H. Schumacher, J. Dederer, B. Schleicher, and A. Trasser

Competence Center Integrated Circuits in Communications
Institute of Electron Devices and Circuits, Ulm University
89069 Ulm, Germany
hermann.schumacher@uni-ulm.de

Abstract— Impulse-radio ultra-wideband (I-UWB) systems for sensing and communications offer very low power consumption, and allow precise radar and location sensing alongside with communications. Therefore, they are interesting candidates for medical applications. This paper reports on the development of a complete I-UWB chipset, consisting of pulse generators, low-noise amplifiers, and correlators aiming at the implementation of a medical application test bed.

Keywords—Si/SiGe, MMIC, UWB, medical applications

I. INTRODUCTION

The US Federal Communications Commission opened up the spectrum from 3.1 to 10.6 GHz to a new class of wireless devices with ultrawide emission bandwidth, yet low spectral power density, able to coexist with narrow-band applications already in place in this frequency band. Similar regulations are under consideration in other countries, albeit not always with the same generous spectral width. One possible approach to utilizing the allocated spectrum is impulse-radio ultra-wideband (I-UWB), a carrier-less modulation format where short time-domain waveforms are being generated and radiated.

I-UWB systems can have a great architectural simplicity and very low power consumption, if the necessary signal

processing on the receiving side is done in analog circuit blocks. Further, the transmitted waveforms of short duration lend themselves to radar sensors and similar location services with sub-millimeter resolution.

Medical technology is an area where I-UWB systems can be used with great benefit. The potential for low power consumption is important for communicating with implanted sensors and actuators, such a cochlear implants, while high-resolution radar imaging is interesting for monitoring the mechanical movement of organs (breathing, heart), as well as in tumor detection.

This paper describes the development of a chipset aimed at the creation of I-UWB medical applications. Key features are high performance, high compactness, and the use of an inexpensive Si/SiGe heterostructure bipolar technology. All building blocks are suitable for combination into more complex multi-functional ICs, an effort which is presently under way.

II. SYSTEM CONCEPT

The block diagram of an I-UWB radar sensor utilizing the chipset is shown in Figure 1. Its core component is the pulse generator, see section IV.A, which is used to generate the transmitted waveform, and also to generate the template pulses for the correlation receiver. Preferably, the spectral requirements should already be approximated by the generator itself and not rely strongly on external filtering. This increases the efficiency of the pulse generator and also reduces size - filter structures, especially when realized on-chip, are necessarily lossy and area-consuming. It has been shown [2] that the fifth derivative of a Gaussian monopulse has a spectrum in good agreement with the FCC indoor mask, which is assumed to apply to medical applications here, see Figure 2.

The necessary phase adjustment between the transmitter and the template pulses for the correlation reception is performed between the clocks feeding the pulse generators, obviating the need for a wideband adjustable true time delay.

Figure 1: Block diagram of the proposed I-UWB radar system.

Figure 2: FCC spectral masks for indoor and outdoor systems, in comparison with the spectral envelope of 5th and 7th derivative Gaussian monocycles.

The received signals are amplified in a wideband low-noise amplifier, which exhibits a flat gain and highly linear phase over the full 3.1-10.6 GHz spectrum. The correlation function is achieved by feeding the LNA output signal and the template pulse into a four-quadrant multiplier, whose output is then integrated, or low-pass filtered.

III. MMIC TECHNOLOGY

All ICs described here were realized in a Si/SiGe heterojunction bipolar transistor foundry process, commercially available from Atmel Germany GmbH, with a high and constant Ge profile in the base [3], which allows for high base doping concentration and correspondingly low base sheet resistances. A benefit of this approach is the ability to reach 80 GHz f_T and f_{max} , with drawn feature sizes of 0.8 μm (effective emitter width 0.5 μm). The process offers three metallization layers, four resistor and two capacitor types. Using a selective implant, high- f_T (80 GHz f_T , 2.4 V BV_{CEO}) and high-breakdown (50 GHz f_T , 4.3 V BV_{CEO}) can be combined on the same chip.

All circuits were realized on standard 20 Ωcm Silicon substrates.

IV. CHIPSET DESCRIPTION

A. Pulse Generator Circuits

As discussed, the pulse generator should generate the fifth derivative of a Gaussian monopulse. The concept is shown in

Figure 3: Concept of the pulse generator.

Figure 3. The incoming signal traverses a limiting amplifier which establishes the rise time and amplitude irrespective of the feeding waveform and is then differentiated. The resulting waveform drives a current switch (a single bipolar transistor) which triggers a transient in the lossy resonant circuit formed by the elements L , C , and R_L . With properly chosen parameters, this results in a close approximation of the intended fifth derivative Gaussian monocycle [4].

Figure 4: Chip micrograph of the pulser IC.

This simple pulse generator approach results in a very compact layout, which is shown in Figure 4. The total chip area is only 0.31 mm².

The received signal, which has undergone further spectral shaping by the antennas (in our case, broadband planar monopoles), more closely resembles the seventh derivative of a Gaussian monocycle. Strictly speaking, the seventh derivative should be used as the template signal in the receiver, however the deviations between the generated waveform and the seventh derivative are quite small and do not result in a large penalty. Figure 5 compares the generated waveform with a theoretical seventh-derivative waveform.

Figure 5: Measured generated waveform (solid) and theoretical seventh-derivative waveform (dashed curve).

B. Low-Noise Amplifiers

The 3:1 frequency ratio between the upper and lower limits of the FCC mask impose a significant challenge on low-noise

amplifier design. Reactive noise matching techniques cannot be used; as the correlation detection concepts relies on close similarity of waveforms, gain and group delay must show little variation within the 3.1-10.6 GHz band. The latter, in particular, makes inductive peaking techniques difficult to apply.

Figure 6: UWB LNA chip micrograph.

A solution relying solely on proper transistor scaling and feedback is presented here, which eliminates all inductors and results in an extremely compact layout, see Figure 6. The total chip area is only 0.13 mm².

Figure 7 shows the circuit schematic. The core of the LNA is formed by a cascode stage which allows for a high open loop voltage gain $A_0=29.9$ dB. Parallel feedback is employed, formed by resistor R_2 and the level-shift diode formed by transistor T_3 . R_2 is chosen so that the input return loss and the transmission bandwidth requirements are simultaneously met. The worst-case input return loss is 8 dB, the 3-dB bandwidth extends from DC to 13 GHz. The closed-loop gain within the UWB confines is 19 ± 0.7 dB, with extremely linear phase. The LNA consumes 36 mW.

Figure 7: Circuit schematic of the UWB low-noise amplifier in Figure 6.

Figure 8 shows the measured noise figure of the amplifier for a 50 Ω generator impedance. The noise figure is 2.2 dB for most of the band, before climbing to its worst-case value of 2.6 dB above 8 GHz. This makes this LNA the amplifier with

the lowest worst-case noise figure on Silicon published so far. It is described in more detail in [5].

Figure 8: Noise figure of the UWB LNA vs. frequency, for 50 Ω generator impedance.

C. Correlator Circuits

The last IC to be described is the correlator, whose schematic is shown in Figure 9. At the core, a Gilbert cell topology is used, complemented with on-chip baluns for the RF port (interfacing with the low-noise amplifier) and the template signal (TS) port, which connects to the pulse generator output, and differential output buffer with 800 MHz low-pass characteristic. Unlike in standard mixer operation, the pulse amplitude applied to the switching quad is adjusted such that the Gilbert cell acts like a four-quadrant analog multiplier. The necessary gain and group delay flatness across the UWB band is adjusted with the capacitively shunted resistive emitter degeneration within the Gilbert cell. Due to the capacitively decoupled inputs, the mixer has a lower cutoff frequency of 3.5 GHz on the RF and TS ports. The upper 3 dB frequency significantly exceeds the UWB band. The mid-band single-ended gain of the correlator is -4 dB, with a power of -5 dBm applied to the TS port, the input 1-dB compression point is -1 dBm. The overall chip size, including bond pads, is 0.33 mm², the total power consumption is 85 mW, of which 27 mW are consumed in the output buffers.

In the system experiment described in the next section, the multiplier output is connected to an active low-pass with a

Figure 9: Schematic of the analog multiplier with on-chip baluns, used in the UWB correlator.

standard operational amplifier, which also performs the differential-to-single-ended conversion for the baseband.

V. SYSTEM VALIDATION

Several system validation experiments have been performed using the chipset described.

Figure 10: Correlation signal obtained on a moving metal target (antenna to target separation: 30 cm, movement amplitude 1 mm).

In the first experiment, the target is a metal plate of approximately 120 x 150 mm² which can be moved accurately on a linear sled moved by an eccentric disc and drive shaft arrangement. While the target is stationary, the phase shift between transmitter and receiver is adjusted for maximum signal at the correlator output. When the plate is moved back and forth, the correlator output exhibits the periodic fluctuations shown in Figure 10. In this case, the target at a distance of 30 cm from the antennas moved by only 1 mm. The correlator output shows this movement with still reasonable signal to noise ratio - the true resolution will be hence lower than 1 mm. It should be noted, however, that due to the multiple maxima in the transmitted signal the result is not unambiguous, but this can be neglected for the specific application, which is the detection of breathing patterns and heartbeats.

Figure 11: Correlator output signal with antennas pointed at the thorax of a test person breathing normally.

Radar measurements on biological targets have also been performed. In Figure 11, the antennas were pointed at the thorax of a test person breathing normally. The correlation signal clearly shows the breathing pattern. This measurement has immediate applications to intensive care monitoring, replacing thorax impedance measurement techniques, which require electrodes to be placed on the patient.

The detection of heart beats is more difficult, because the movement amplitudes are lower, but especially because of the strong added attenuation between the thorax wall and the heart muscle. In our first measurements, a signal with the correct frequency was detected, but its origin (induced thorax movement or movement of the heart muscle) will have to be ascertained.

VI. CONCLUSIONS AND OUTLOOK

We presented a full chipset for impulse-radio UWB sensors, consisting of pulse generator, low-noise amplifier, and multiplier/correlator. First trial measurements were performed on metallic targets and on test persons, confirming the correct operation of the system and its excellent distance resolution < 1 mm. Currently under way is the full monolithic integration of the UWB receiver, as well as efforts at improved signal processing on the correlator signal to further improve the sensitivity. Additional evaluations in medical settings are also planned

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