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A Fully Monolithic 3.1-10.6 GHz UWB Si/SiGe HBT Impulse-UWB Correlation Receiver

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***Abstract*—A 3.1-to-10.6 GHz Impulse-UWB correlation receiver in a 0.8 μm Si/SiGe HBT technology is presented. The fully monolithic receiver with $0.8\,\mathrm{mm}^2$ chip size comprises a low-noise amplifier with maximum noise figure of 3.2 dB, two single-ended to differential converters, an analog correlator and a template pulse generator approximating the fifth-derivative of a Gaussian impulse. It operates with pulse repetition rates up to 900 MHz (IF bandwidth limited) with a total power consumption of 200 mW.**

I. Introduction

Low complexity, sub-optimal Impulse-UWB (I-UWB) correlation receivers have gained momentum in low data rate applications in the low 3-to-5 GHz frequency band, e.g. [1],[2]. In case of sub-optimal correlation, the locally generated template waveform is not an exact replica of the received waveform which is given by the convolution of the transmitted pulse with the time-variant channel impulse response. The resulting degradation in receiver performance is accepted to keep the architecture simple. Compared to low-band 3-to-5 GHz operation, full-band 3.1-to-10.6 GHz I-UWB correlation reception has potential advantages with regard to radar resolution capability, sensitivity and transmission data rates. However, the broad bandwidth imposes great challenges on the low-noise amplifier (LNA), the correlator and particularly on the generation of appropriate template pulses. In this work we present an innovative, fully monolithic 3.1-to-10.6 GHz I-UWB correlation receiver which can be operated in a large variety of I-UWB applications, including communication and high-resolution radar and sensing systems.

II. MMIC architecture

The architecture of the fully monolithic single-band I-UWB correlation receiver is depicted in Fig. 1. The input stage of the MMIC is a single-ended three-stage LNA which is followed by a single-ended to differential converter. Correlation reception is achieved by feeding the LNA output signal and the template signal (TS) into a differential four-quadrant multiplier whose output is passed through a differential output buffer with 900 MHz low-pass characteristic. Wide-band, four-quadrant multiplication is accomplished by a fully-balanced Gilbert-cell topology with capacitively shunted resistive emitter degeneration [3]. The LNA uses a combination of intra- and inter-stage feedback networks to broaden the bandwidth in terms of noise performance, input return loss, gain and group delay flatness. On-wafer measurements of the LNA in a $50\,\Omega$ test environment show a gain of 23.2 ± 0.3 dB, a worst case input return loss of 8.5 dB and a maximum 3.2 dB noise figure across the full 3.1-to-10.6 GHz band [4]. The necessary phase adjustment between the incoming waveforms and the template pulses is performed with the clock feeding the template pulse generator (CLK_{TS}) which obviates the need for a wideband adjustable true time delay. The transmitter and the receiver are tightly synchronized with a common reference (f_{ref}). The latter is applicable in radar and sensing applications where the transmitter and receiver are co-located while the situation is more complex in communication systems which require a synchronisation of the remote receiver.

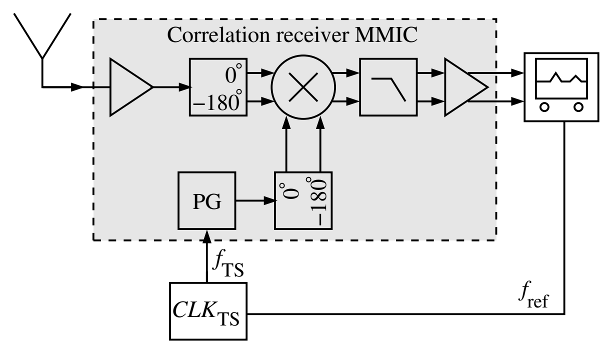

Fig. 1. Architecture of the fully monolithic single-band IR-UWB correlation receiver

As stated earlier, the locally generated template pulse does not attempt to estimate the received waveform. Instead, it resembles the fifth derivative of a Gaussian impulse which, with appropriate σ, has a spectrum in good agreement with the FCC indoor mask, lending itself as a central building block in single-band UWB transmitters. Fig. 2 shows the corresponding power spectral density of a continuous 200 MHz fifth-order derivative Gaussian monocycle pulse train and its compliance to the allocated spectrum mask for indoor UWB. The template pulse shape is accomplished by the transient of a lossy resonant circuit formed by the elements L, C and the load $\mathrm{R_L}$ presented by a resistive matching network which connects to the succeeding single-ended to differential converter as shown in Fig. 3. The resonant circuit is triggered by a short pulse of 83 ps full width at half maximum. The latter is formed by passing the clock signal through a two-stage limiting amplifier

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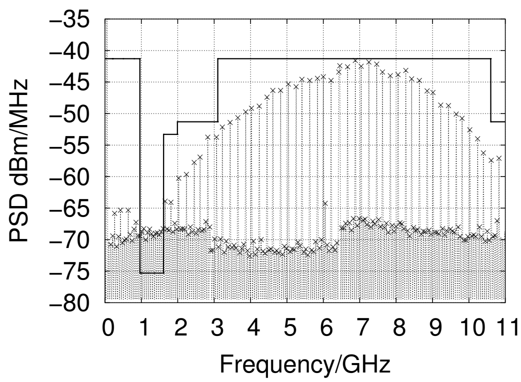

Fig. 2. Measured PSD of a 200 MHz fifth-order derivative Gaussian monocycle pulse train (-x) in comparison with the FCC spectral mask for indoor UWB systems

and differentiating its output. The limiting amplifier ensures an easy application of the chip as it establishes the required amplitude and rise time irrespective of the feeding waveform.

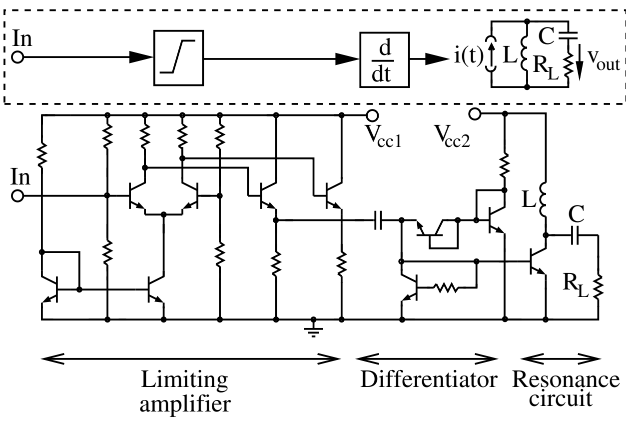

Fig. 3. Block diagram and simplified circuit schematic (only one stage of limiting amplifier depicted) of pulse generator

A micrograph of the receiver MMIC is shown in Fig. 4. Despite the fact that the MMIC operates over a relative bandwidth of more than $100\,\%$, only one spiral inductor is present in the whole design which results in the extremely small chip size of $0.8\mathrm{mm}^2$.

The receiver MMIC is operated from a 3 V and an adjustable 4-to-6 V supply where the latter controls the amplitude of the template signal. In continuous, steady-state operation from a 3 V and 4.5 V power supply, the correlation receiver exhibits a total power consumption of approximately 200 mW which is almost independent of the applied pulse repetition rate. The demand for low-power consumption can be met by making use of the typically low duty cycles of I-UWB applications. Compared to a carrier-based UWB receiver, the single-band I-UWB receiver does not require local-oscillator and PLL startup and settle periods, which enables a short start-up time of the receiver. From this, the receiver MMIC can be aggressively duty-cycled, resulting in a significantly reduced

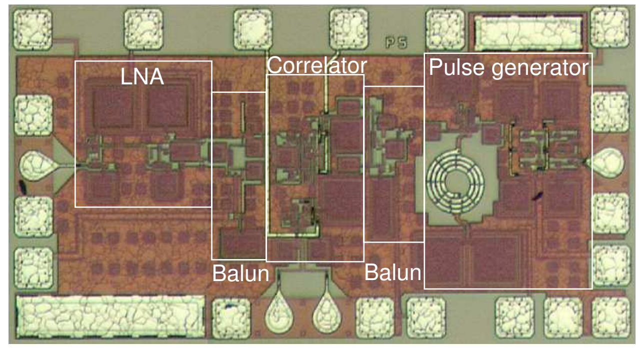

Fig. 4. Micrograph of the single-band I-UWB correlation receiver

power consumption compared to a continuous, steady-state operation.

III. MMIC TECHNOLOGY

The correlation receiver MMIC has been realized in a low cost Si/SiGe heterojunction bipolar transistor foundry process with minimum 0.8 μm drawn feature size [5]. Using a selective collector implant, high $\mathrm{f_T}$ (80 GHz $\mathrm{f_T}$, 2.4 V $\mathrm{BV_{CEO}}$) and high breakdown (50 GHz $\mathrm{f_T}$, 4.3 V $\mathrm{BV_{CEO}}$) transistors can be combined in a single chip. The process offers three metallization layers, four different types of resistors and dielectric MIM capacitors as well as nitride capacitors. The passive and active devices are realized on a standard 20 Ωcm p-type substrate.

IV. OPERATING BANDWIDTH AND CONVERSION GAIN

Operating bandwidth and conversion gain of the mounted receiver are derived from a test chip where the template pulse generator has been omitted to allow sinusoidal inputs at the LNA as well as at the TS port of the correlator. A non-zero IF frequency f_{IF} of 100 MHz is chosen which is well below the upper IF cut-off frequency. Fig. 5 illustrates the measured differential conversion gain for an RF power of -30 dBm with various values of applied template signal (TS) power where all power levels are corrected to the MMIC in- and output reference planes. The receiver has its conversion gain maximum around 6 GHz with gain variations of $\pm\,2$ dB within a 4 GHz to 10 GHz bandwidth.

V. RECEIVER VALIDATION WITH IDEAL CHANNEL

Prior to measurements with radiated and received pulse trains, a fifth-derivative monocycle pulse generator module was connected to the mounted receiver MMIC via a variable attenuator which emulates an ideal channel with an adjustable propagation loss. The applied transmit (TX) pulse generator is based on the same circuit topology as used for the on-chip template pulse generator. Both pulse generators are operated with identical pulse repetition rates.

A. Correlation detection

In a first experiment, the differential correlator transient outputs are captured with an equivalent-time sampling scope and post-processed with software. Fig. 6 compares the measured

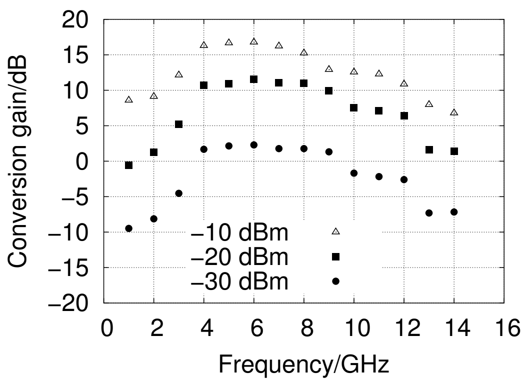

Fig. 5. Downconversion to fixed $f_{\mathrm{IF}} = 100\,\mathrm{MHz}$ with applied RF power of $-30\,\mathrm{dBm}$ for various values of applied TS power.

correlation with the calculated auto-correlation of ideal fifth-order derivative Gaussian monocycles which make efficient use of the allocated spectrum mask [6]. Excellent agreement between theory and measurement has been achieved, proving the necessary gain and group delay flatness of the MMIC.

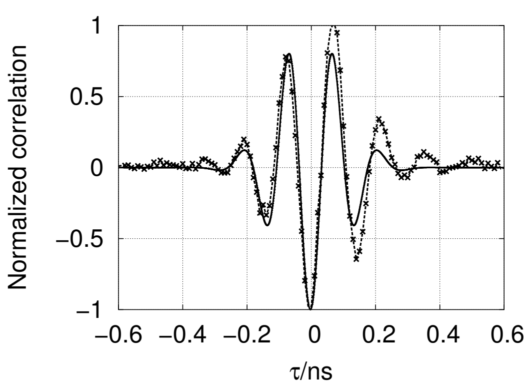

Fig. 6. Normalized ideal auto-correlation of fifth-order derivative Gaussian monocycles (solid line) compared to measured correlation (-x-)

B. Minimum discernable signal

Receiver sensitivity is approximated by the minimum discernable signal (MDS) which is the smallest input signal level to the receiver that will produce a discernable output signal. Here, the MDS is defined as the mean input power level which is necessary to obtain a correlator DC output voltage equivalent to the RMS noise voltage at the correlator output where the latter is referred to a chosen IF bandwidth (see below). Measurements of the DC-content of the correlator transients imply one pulse per symbol, or, in other words, a symbol rate equivalent to the pulse repetition rate. In general, the correlator DC output voltage depends on the received instantaneous pulse power and the pulse repetition rate. For the sake of generality, the MDS is determined as a function of the mean input power level as the latter implies both, the instantaneous pulse power as well as the pulse repetition rate. All measurements are performed with continuous pulse trains with 200 MHz pulse repetition rates with optimum time alignment of the template pulses. Measurements of correlator DC output voltages and RMS noise voltages are carried out with $50\,\Omega$ terminations at both outputs. Fig. 7 shows the differential correlator DC output voltage versus mean input power in double-log scale.

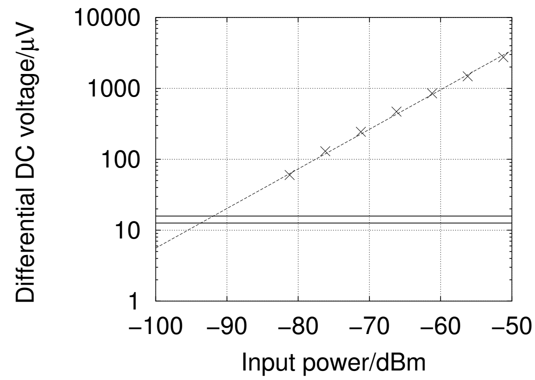

Fig. 7. Measured differential correlator DC output voltage (x) with $50\,\Omega$ terminations at both outputs versus mean input power in double-log scale. For the evaluation of the MDS, a linear regression line (dotted line) and the approximated minimum and maximum RMS noise amplitudes ($V_{\mathrm{RMS,Noise}} = 14.2 \pm 1.6\,\mu\mathrm{V}$, 100 kHz IF bandwidth) are included

The RMS noise voltage at the receiver output is evaluated with a Stanford Research Systems lock-in amplifier SR830. For the measurements of the RMS noise voltages, the template pulse generator is operating with continuous pulse trains of 200 MHz pulse repetition rate while the TX pulse generator is turned off. The measured $V_{\mathrm{RMS,Noise}}$ value is independent of the applied template pulse repetition rate and exhibits a noise amplitude of $V_{\mathrm{RMS,Noise}} \approx 45 \pm 5 \frac{\mathrm{nV}}{\sqrt{\mathrm{Hz}}}$ at the correlator output. From this, the $V_{\mathrm{RMS,Noise}}$ noise amplitude within an exemplarily chosen IF bandwidth of 100 kHz can be approximated to $14.2 \pm 1.6\,\mu\mathrm{V}$ where the increase of $V_{\mathrm{RMS,Noise}}$ below 10 kHz (due to $\frac{1}{\mathrm{f}}$ flicker-noise) is neglected. The MDS is approximated by a linear regression line in double-log scale. In case of a 100 kHz IF bandwidth, the MDS can be approximated to $-92.8\,\mathrm{dBm} \pm 0.9\,\mathrm{dB}$ (see again Fig. 7).

VI. Receiver validation with radiated pulse sequences

Measurements with radiated and received waveforms were done in an anechoic chamber with the TX and RX antenna placed at a distance of 15 cm. The UWB antennas are based on a square planar monopole. To achieve the maximum impedance bandwidth using a simple square monopole, a pair of notches is placed at the lower corners of the patch where the notch structure is embedded in a truncated ground plane. A detailed description of this approach is given in [7]. Fig. 8 shows the measured correlation with a radiated and received fifth-derivative Gaussian monocycle. The received pulses also contain the impulse responses of the antennas which add to that of the channel. However, as shown in Fig. 8, the deviations compared to the correlation in case of an ideal channel (Fig. 6) are notably small and do not result in a large penalty in receiver performance which underpins the concept of a sub-optimal correlation receiver for short-range, line-of sight connections.

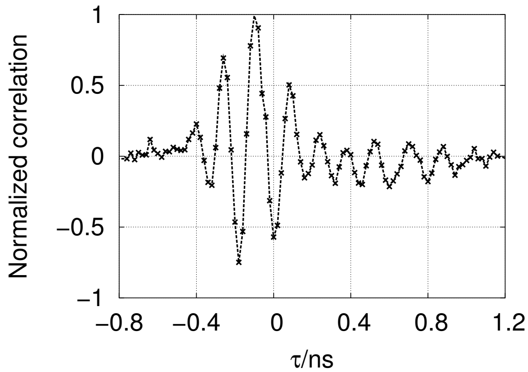

Fig. 8. Normalized cross-correlation with radiated fifth-order derivative Gaussian monocycles

A. Data communications

The pulse generator concept applied on the TX as well as RX side requires a return-to-zero modulation as the pulses are generated on the transition from a logical zero state to a logical one state as illustrated in Fig. 9. The corresponding correlation transients of the transmitted, periodically repeated data sequence (Fig. 9) with manually adjusted time synchronisation are depicted in Fig. 10. The TS-feedthrough, which is observed for a received logical zero bit, negatively affects the MDS. However, as the TS-feedthrough contains almost equal positive and negative signal components, integration over the chip period will alleviate the problem. Here, the receiver MMIC is demonstrated with an elevated data rate of 800 Mb/s. In future applications, the data rate can be adapted to channel conditions, e.g. the time interval between two consecutive pulses has to be larger than the longest expected channel impulse response of the multipath environment to avoid inter-pulse interference due to multipath propagation.

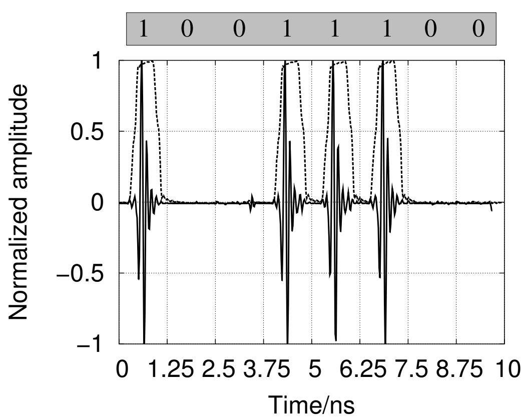

Fig. 9. Return-to-zero OOK concept. Normalized data input (transmitted data pattern) and corresponding pulse sequence (measured at TX pulse generator output, 800 Mb/s OOK modulation), both normalized to maximum amplitude

VII. Conclusion

We presented a fully monolithic correlation receiver for single-band, 3.1-to-10.6 GHz impulse UWB. The receiver is realized in a low cost, commercially availabe 0.8 μm Si/SiGe HBT technology and comes at an extremly small chip size of 0.8 mm^2. The receiver MMIC comprises a fifth-order derivative Gaussian monocycle template pulse generator, a low noise amplifier, two single-ended to differential converters, a four-quadrant Gilbert cell multiplier and an additional buffer amplifier with 900 MHz low-pass characteristic. The excellent performance together with the inherent low complexity make the MMIC an ideal candidate for short-range communication as as well as high-resolution radar and sensing systems.

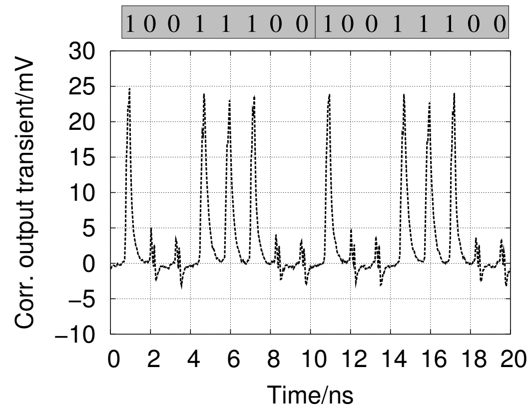

Fig. 10. Correlator output transients (recovered data pattern) for a radiated and received 800 Mb/s OOK modulated data sequence

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