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A Fully Differential IR-UWB Front-end for Noncoherent Communication and Localization

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Abstract—This paper presents a 3.1-10.6 GHz ultra-wideband transmitter/receiver chipset for non-coherent communication and localization applications. Its fully differential topology fits promising balanced UWB antennas, and eases packaging. The transmitter uses a cross-coupled oscillator core transiently turned on by a current spike. It consumes 6 mW at 100 MHz impulse repetition rate, including the on-chip pulse shaping circuitry. The energy-detecting receiver front-end combines a fully differential low noise amplifier (LNA), a differential squaring circuit, low pass filters and buffers. The complete receiver IC dissipates 108 mW, almost independent of the applied impulse rate. Transmit and receive ICs are mounted chip-on-board at the feedpoints of dipole fed circular slot antennas. The measurement results suggest communication speeds up to 700 MBaud using on-off keying.

I. INTRODUCTION

Single-band impulse radio ultra-wideband (IR-UWB) systems utilize carrier-less modulation formats with sub-nanosecond pulses to take advantage of wideband frequency allocations (here, 3.1-10.6 GHz) with low spectral power density (here, -41.3 dBm/MHz). The large spectral bandwidth offers significant advantages in high-resolution radar and high-speed data communications[1], while the carrierless nature allows low power consumption and simple transmitter and receiver architectures.

Several different IR-UWB receiver architectures have been published, including analog correlation [2], [3], acting like a matched-filter receiver when operated with a properly synchronized template signal, and non-coherent energy detection. Previous works [4], [5] used single-ended circuit topologies, and employed the 3-5 GHz low band. While correlation receivers show better performance as they are less sensitive to noise and particularly interference, they require exact synchronization, rarely realized in communication and time difference of arrival (TDoA) applications (as opposed to radar). Although non-coherent detectors are suboptimal, they eliminate the need for synchronization and have simpler architecture leading to lower power consumption.

We present a fully differential UWB RF transmitter/receiver chipset for non-coherent applications, addressing the whole FCC band. Differentially fed antennas avoid radiation from the outer shield of unbalanced feed lines, which strongly favors

differential topologies for UWB circuits, eliminating the need for ultra-wideband baluns. Additionally, the on-chip virtual ground inherent to the fully differential topology eases packaging as it effectively decouples common-node impedances in ground and supply voltage connections. While differential circuits do consume more power, this disadvantage is offset by the elimination of active baluns, and in this work by a highly efficient impulse generator concept.

II. SYSTEM CONCEPT

Fig. 1. Architecture of the proposed UWB system based on energy detection

The block diagram of the non-coherent transceiver is shown in Fig. 1. The transmitter is formed simply by the UWB impulse generator IC and an antenna. The IC generates nanosecond duration impulses with variable repetition rates into the GHz range, whose spectrum fits the FCC indoor spectral mask well.

On the receiver side, the incoming impulses are first amplified by a wideband differential LNA. Then, pulse energy is detected by squaring and low-pass filtering, with subsequent amplification. Both transmitter and receiver modules use broadband dipole fed circular slot antennas [6].

The base-band signal can then be further processed in either the analog or digital domain, and may also be used for precise TDoA localization, similar to [7].

III. TECHNOLOGY

All active circuits were realized in Telefunken Semiconductors GmbH SiGe2RF 0.8 μm HBT technology [8]. It offers npn transistors either with high f_T ($f_T = 80$ GHz, $BV_{CEO} = 2.4$ V)

or with high breakdown voltage ($f_T = 50 \text{ GHz}$, $BV_{CEO} = 4.3 \text{ V}$) on the same chip using selective collector implants. The process incorporates three metallization layers, four different types of resistors and dielectric MIM capacitors. All the devices were fabricated on a low resistivity $20 \Omega \text{ cm}$ substrate. The process was chosen as it offers more than adequate performance for UWB applications at very reasonable cost, even for small production volumes.

IV. CIRCUIT DESIGN

A. Differential impulse generator

This impulse generator was discussed in detail in [9], but is briefly explained here for clarity. The impulse generator

Fig. 2. The complete circuit schematic of the differential impulse generator

has three main functional blocks, see Fig. 2. The Schmitt trigger steepens the rising edges of the incoming base-band signal (V_{BB}), whose exact signal shape thus does not matter. Transistor T_1 is biased in off state, while the output voltage of the Schmitt trigger is low. When a rising input signal turns T_1 on, T_2 shuts off and its collector potential increases immediately. Eventually, the diode-configured transistor T_3 will bring that potential down to the built-in base-emitter potential of T_4 , with a time constant determined by R_1 and the base-emitter capacitance C_{BE3} of T_3 . So the collector potential of T_3 has a spike-like shape before it settles, and this correspondingly generates a collector current spike in T_4 . The area ratio of T_3 and T_4 is chosen such that T_4 will not supply sufficient current to the cross-coupled oscillator core to turn it on, except during the current spike.

The LC oscillator is activated when the collector currents of the cross-coupled pair (T_5 and T_6) are sufficient to create a negative real part of the impedance at their collector terminals. A deliberate asymmetry (R_2 and R_3 are different) is introduced for a fast start-up. The purpose of R_4 is to quench the oscillator more rapidly immediately after the decay of the current spike. Thus, short oscillatory pulses will appear at the output, whose intrinsic frequency is defined by the oscillator resonant circuit, and whose duration is set by the current spike. The measured impulses with a 100 MHz sinusoidal input signal are given in

Fig. 3. The results show a peak-peak amplitude of 210 mV and an envelope width of 0.3 ns FWHM. The spectrum of

Fig. 3. Measured output impulse train with 100 MHz repetition rate

the corresponding measured impulse train can be seen in Fig. 4. It has a large 10-dB bandwidth of 4.9 GHz well fitting the FCC spectral mask. The impulse generator has a power consumption of 6 mW for generating this 100 MHz impulse train. The differential impulse generator is mounted chip-on-

Fig. 4. Comparison of the measured power spectral density (PSD) with FCC regulatory mask

board at the feedpoints of a dipole fed circular slot antenna, as shown in Fig. 5.

Fig. 5. The realized transmitter and the IC of the differential impulse generator

B. Differential LNA

Fig.6 shows the schematic of the differential LNA. It

Fig. 6. Schematic of the differential LNA

consists of a highly symmetric emitter-coupled cascode pair emitter follower buffers. A current mirror biases the cascode stage. Only the left half-circuit of the emitter-coupled pair will be discussed here, since the right part is identical. Common-emitter transistor T_1 and T_3 in common base topology form the cascode, reducing the Miller capacitance at the input of T_1 and enhancing the bandwidth. The shunt-shunt feedback (R_1 and C_1) further broadens the bandwidth and provides broadband input match simultaneously. Input transistor size and bias point are chosen as a compromise between optimum current density for minimum noise figure, an input impedance close to noise match, and achievable bandwidth. The emitter length of T_1 is chosen to be $24.7 \mu m$, while the emitter current is 5 mA.

Fig. 7. Measured S-parameter magnitudes of the differential LNA

The two emitter follower buffers provide high input impedance for a good inter-stage match and lower output impedance to match the load. Capacitively compensated resistive emitter degeneration in the buffers improves the bandwidth. Differential S-parameters were measured using two identical microstrip line UWB baluns and are shown in Fig. 7. The amplifier show a maximum gain of 19.9 dB with a 1.8 dB

variation over the whole FCC band from 3.1 to 10.6 GHz. Return loss is below -7 dB, at the input, below -6 dB at the output within the complete frequency range. The differential

Fig. 8. Measured single-ended and extracted differential noise figures of the LNA

noise figure is extracted from single-ended measurements [10]. First, the single-ended noise figure F_{31} from port $Out-$ to $In+$ was measured with the other ports terminated by 50Ω loads. Then, the transducer gain from $Out-$ to $In+$ (G_{31}) and $Out+$ to $In+$ (G_{32}) was measured. Due to the symmetry of the LNA, the differential noise figure can be calculated as

$$F_{diff} = 1 + \frac{1}{G_{31} + G_{32}} (F_{31}G_{31} - G_{31} - G_{32}). \quad (1)$$

Fig. 8 shows both the measured single-ended and extracted differential noise figures. The differential noise figure varies from 2.1 to 2.9 dB within the entire band. The measured input 1-dB compression point at 7 GHz is -17.5 dBm. The circuit draws a DC current of 22 mA from a 3.5 V supply.

C. Energy detection circuit

Fig. 9 shows the schematic of the wideband energy detection circuit. At the core, a Gilbert-cell analog four quadrant

Fig. 9. Schematic of the wide-band energy detector with squaring device, low pass filter and a differential buffer

multiplier comprising two differential stages in parallel with cross-coupled output is complemented by a low pass filter and a differential output buffer. The squaring operation is realized by connecting the same signal to both inputs. The differential buffer of the LNA stage is reused here to split the signal path, which saves power. The unbuffered input signal is fed to the lower pair, while the buffered input signal feeds the top quad. The combination of C_E with R_E forms a capacitively shunted resistive emitter degeneration compensating the gain roll-off at high frequencies, which in turn achieves the necessary gain flatness over the whole UWB frequency band. The input buffer and the lower pair of the Gilbert-cell introduce almost the same group delay. Thus, the two branches of the input signal arrive simultaneously at the multiplier. Fig. 10 exhibits a comparison of the output waveform of the squaring circuit and the input UWB impulse. The basic squaring operation is visible by the simulated output signal.

Fig. 10. Simulated normalized time-domain output of the squaring circuit and the input UWB impulse

Low pass filters with 1 GHz 3-dB bandwidth are formed by the load resistors (R_1, R_2) of the Gilbert cell, together with shunt capacitors (C_1, C_2) of the output buffer. The low pass filter allows the detection of the squared pulse's envelope. The power consumption of the energy detection circuit is 73 mW (where 42 mW is shared with the LNA). The receiver front-end is mounted on a 0.81 mm thick Rogers RO4003C substrate, which also carries the dipole feed structure, and is wire-bonded to microstrip transmission lines feeding the antenna and providing the output signals, as shown in Fig. 11. The size of the receiver front-end IC is 0.26 mm^2 , including bond pads.

V. SYSTEM VALIDATION

A transient measurement in the E-plane of the described transmitter is provided in Fig. 12. The picture shows the measured normalized voltage amplitude against azimuth angle and time. The information between -0.2 and 0.3 ns clearly shows the multi-cycle transit in time domain. It can be seen

Fig. 11. The receiver and the IC of the receiver front-end including the LNA and the energy detection circuit.

that differential antenna has a wide beamwidth, which is helpful for localization applications. An impulse train with

Fig. 12. Normalized received amplitude against H-plane rotation angle and time of the discussed transmitter

700 MHz pulse repetition frequency was transmitted over a distance of 35 cm, using the described modules. The result are shown in Fig. 13. The top graph shows the output directly measured at the transmitter, while the bottom graph shows the received signal at the output of the receiver IC. Given that the pulses are cleanly resolved, this experiment is indicative of a communication speed of 700 MBaud, using on-off keying. The transmitter consumes 7.5 mW in this mode of operation. The impulse rate can be readily adjusted and hence is very easily adapted to changing channel conditions, e.g. to avoid errors due to multipath interference.

VI. CONCLUSION

A fully differential chipset for non-coherent communication and localization applications using impulse radio ultra-wideband was presented, utilizing the full bandwidth of the FCC mask. The transmitter is based on a pulsed cross-coupled oscillator concept, and has a very low power consumption.

Fig. 13. Measured results of the (top) output of the differential IG and (bottom) the output from the receiver front-end with the TX and RX placed with a distance of 35 cm.

The receiver uses energy detection, employing a true squaring circuit with a four-quadrant analog multiplier at its core. The fully differential topology is ideally suited for balanced UWB antenna structures, which avoid otherwise notorious problems with finite groundplanes and feedline radiation. Measurement results show that the proposed system can be used for short-range high speed communication and localization applications.

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