Multi-Mode FMCW Radar Array with Independent Digital Beam Steering for Transmit and Receive

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***Abstract*— A phased-array FMCW radar has been design and built from COTS components. The generation of the frequency sweep is done by mixing a central local oscillator signal with a baseband sweep of a direct digital synthesizer (DDS). To ensure maximum flexibility the receive side has been equipped with it's own swept signal. The transmit frequency generation and receive frequency generation are derived from the same local oscillator signal and clock to ensure coherent operation. This architecture makes a very flexible platform as the waveforms can be changed, transmit and receive and be independently programmed and the system is scalable, also by the mechanical outline of the system and antenna.**

I. Introduction

Frequency Modulated Continuous Wave (FMCW) radar is used in many applications due to it's simple architecture. One of the main limitations is a result of the fact that transmitting and receiving occurs at the same moment in time. This is the most striking difference with pulsed radars. The isolation between transmitter and receiver path (in the circulator, or between the antennas) and phase noise of the transmitter are the main limitation for the total transmit power that can be used. However due to the fact that the transmitter is always on the product of power and duty cycle does not have to be very bad compared to pulsed systems.

The FMCW signal generation has been integrated directly into the front-ends of the phased-array radar. Also the digital concept has been used to its full capabilities: the transmit-receive (TR) modules' only high-frequency input is the X-band local oscillator signal. Further a clock, start-sweep and programming interface is present on each TR module.

II. Radar modes

The architecture of this FMCW phased-array radar provides the possibility of setting frequency, phase and amplitude for each element, and for the transmit and receive chain separately. This opens the possibility of several modes of operation.

These modes are:

- single beam on transmit and receive, with digital (adaptive) beam forming [1],
- wide beam on transmit and multi-beam on receive,
- MIMO radar.

If the offset frequency for the direct digital synthesisers is chosen equal in transmit and receive the detection is done at baseband, however this front-end also provides the possibility to use a different frequency and thus detect at a given intermediate frequency (IF). By applying the same settings to the two DDS chips in the same TR module the operation of this radar is equal to that of the former version [1]. A replica of the transmit sweep on transmit is used in receive and thus the baseband bandwidth can be tailored by using the correct combination of frequency sweep bandwidth, time and expected maximum range.

When only one transmit module is used the radar will generate a floodlight beam. This will illuminate a large angular area and detection in angle can be done with multiple staring beams on receive.

For use as multiple-input multiple-output (MIMO) radar the front-end have the freedom to make a predefined waveform for transmit, at a frequency offset from the local oscillator. The receiver will be preset to the same offset from the local oscillator but the received signal will not be demodulated with the exact waveform as in transmit. The signals for MIMO radar will have to be processed digitally per channel.

III. System Description

Mechanically the module can be separated into:

- motherboard,
- 8 TR modules,
- 2 antenna arrays,
- base plate for mechanical support.

The base plate has 16 threaded SMP bullets for connecting the antennas on one side and the TR modules' Tx outputs and Rx inputs on the other side (Fig. 3). The TR modules are also connected to the mother board with 8 local oscillator ports and IF and DC supply headers. The mother board contains all external connections as power, control (RS-232), start sweep, optional external LO and transmit replica for easy antenna pattern measurements. The motherboard is fixed to the base plate which has provisions for mounting on an external support, dust cover and cooling fans. The complete system can be operated from a laptop power supply. Both the motherboard as the 8 TR modules are designed in a standard PCB flow on Rogers 4003 multilayer substrates.

A. Motherboard

The X-band signal for the radar can be externally supplied or generated internally. The external option, selected through a switch on the motherboard, provides the possibility to scale the system to multiple modules while maintaining coherent signals. The internal synthesiser uses a 155 MHz oscillator, phase-locked loop (PLL) circuit and direct digital synthesiser (DDS) to generate a software adjustable local oscillator signal around 10 GHz. This signal is amplified, split in two and distributed to the 8 SMP connectors to connect to the TR modules. The other branch is mixed with a baseband signal from a DDS circuit and supplied to a connector accessible from the outside. The mixer-DDS arrangement is identical to that in the TR modules and when programmed identically it can provide a copy of the transmit signal to, for instance, a reference input of an antenna measurement set-up receiver.

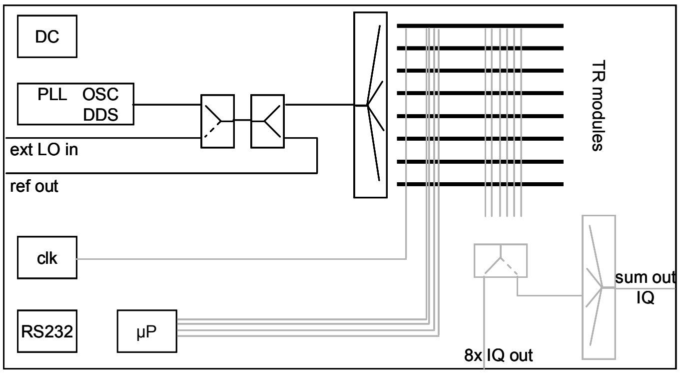

Fig. 1 Schematic drawing of the motherboard.

The IF outputs of the receivers on the TR modules either routed to the 16 individual IQ output connectors for most flexible processing options or terminated in 50 Ω and summed without adjustable phasing to a common output. The common output relies on beam forming by adjusting the phasing of the received signals through the receiver local oscillator.

Other circuitry on the mother board is a microcontroller with RS-232 interface for controlling all DDS and switches as well as the on-board synthesiser.

B. Transmit-Receive Modules

The TR modules contain a single side band mixer for upconversion of the LO signal from the mother board with the signal from the transmit DDS to the swept transmit signal. After amplification to 12.5 dBm this is connected directly the antenna elements. A total effective isotropically radiated power (EIRP) of over 2 W is obtained for an 8-element array.

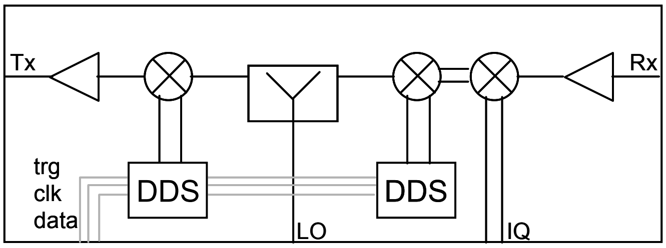

Fig. 2 Schematic drawing of TR module.

In the receiver chain the local LO signal is first mixed with the baseband signal from the receive DDS and subsequently used as the LO signal for down-converting the received signal (after low-noise amplification) from the antenna.

C. Direct Digital Synthesis Technology

Direct Digital Synthesisers (DDS) generate flexible and accurate tones or frequency sweeps. The control is done digitally. Each received clock pulse the DDS adds a predefined value to a phase register, calculates the corresponding amplitude word and feeds this to a digital-analogue converter. The filtered output frequency then corresponds to the predefined linear phase slope, thus constant frequency. Analog Devices AD9958 DDS have been used. They contain two DDS cores which are programmed with a 90° phase offset to generate IQ signals for the single sideband mixers. These devices also offer the possibility to increase the predefined phase offset per clock pulse. This results in a quadratic phase increase and thus a linearly increasing frequency output.

The DDS circuits are operated directly from the external clock signal, bypassing the internal multipliers. This ensures a very acceptable phase noise behaviour. Together with the physically separated antennas, which lowers the transmitter to receiver crosstalk, the radar has sufficient detection sensitivity.

D. Antennas

The system uses two separate 8-element antenna arrays, one for transmit and one for receive. The antennas are fabricated in a standard PCB line.

The antenna panels have angled SMP connectors and feeding lines on one side of the substrate and shallow slot coupled cavities, surrounded by vias, on the other side. The panels are approx. 3 mm thick. The antenna elements are pin-based cavity radiators. The feeding is done with microstrip coupled through a slot in the round plane. The pitch of the antenna elements in the arrays is 14 mm and thus allows for grating lobe free scanning up to 10.7 GHz, or scanning up to 50° up to 12.7 GHz [2].

The edges of the antenna arrays are close to the pin based cavities to allow for aligning multiple substrates to built larger arrays. The element spacing will only be 1 mm larger for elements on different substrates.

The transmit and receive antenna centres are approximately 80 mm apart and are on separate panels.

IV. Beam Steering

Beam steering takes place, depending on the radar mode, in the settings of the transmit DDS or in a generic processor on receive.

For the single beam radar mode each DDS in the transmit chain receives a different start phase word. This result sin phase steering of the antenna elements as the phase is linearly translated from IF to RF. When this signal is copied and used as a swept LO in receive this steers the receiving antenna elements in the same direction [1].

In the system in [1] this is achieved by using a -20 dB coupler after the last amplifier. In this system a signal identical to the transmit signal is generated by mixing the same LO from the motherboard with a DDS signal with identical setting and derived from the same clock and start sweep trigger signal.

Multiple simultaneous beams on receive can be formed when a processor is implemented in e.g. a PC or an FPGA after sampling all 8 receive channels. The DDSs in the receive paths will have identical start phase and phasing of the signals is done in the beam steering processor. The signal on receive are mixed with a swept signal from the DDS, identical to the sweep used in the transmit chain. This reduces the bandwidth to be sampled at baseband. For MIMO processing however the receive channels will be down converted using a fixed LO. This allows for digitally downconverting the signal from each receive element with a different, orthogonal, waveform and on top of that beam steering the receive antenna pattern.

V. Measurement Results

Parts of the system are characterised separately, while the total concept is validated by beam steering the array and measuring it's antenna pattern and applying normal radar data processing to the signals and generating range doppler plots. The detection using range doppler plots will be demonstrated at the live poster session.

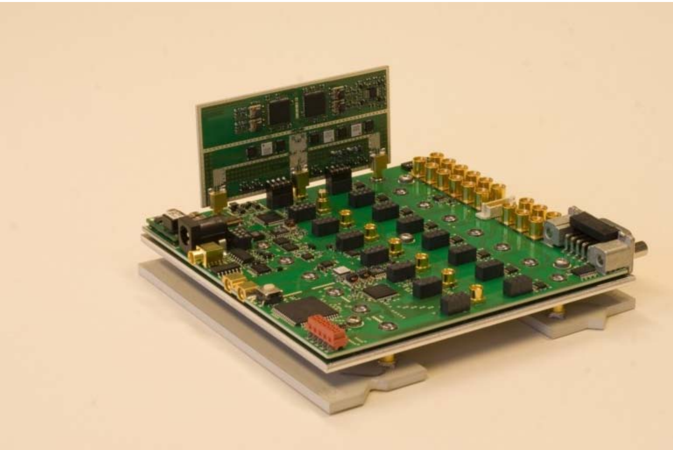

Fig. 3 FMCW array (11x11x5 cm^3): antenna arrays point downward and 7 of the TR modules have been removed to show the motherboard.

The antenna arrays have been measured separately in a near-field facility. The transmit and receive array have been positioned exactly as in the radar system. Therefore also TR coupling could be characterised. This is an important parameter as it can limit the dynamic range of FMCW systems. The matching of the elements in an array configuration is below -10 dB for 8.9-10 GHz. The coupling from Tx-element to Rx-element is below -35 dB for all combinations.

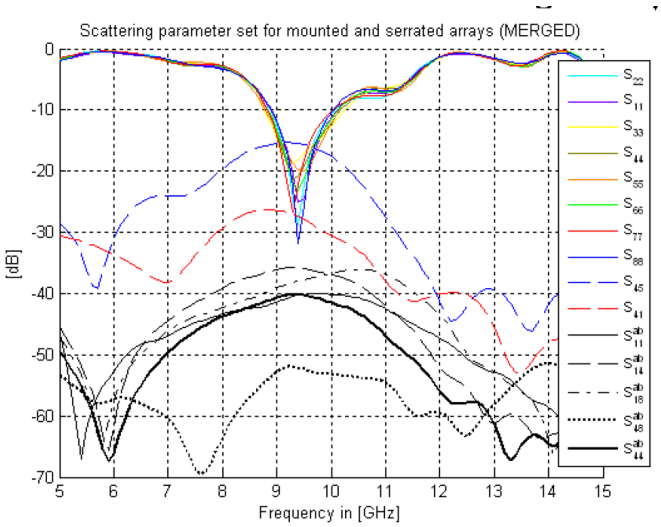

Fig. 4 S-parameter measurements on the antenna arrays mounted in a configuration identical to the radar system.

The transmit chain can be supply 12.5 dBm at the antenna element connector. The power can be varied over approx. 50 dB by proper settings in the DDS circuit.

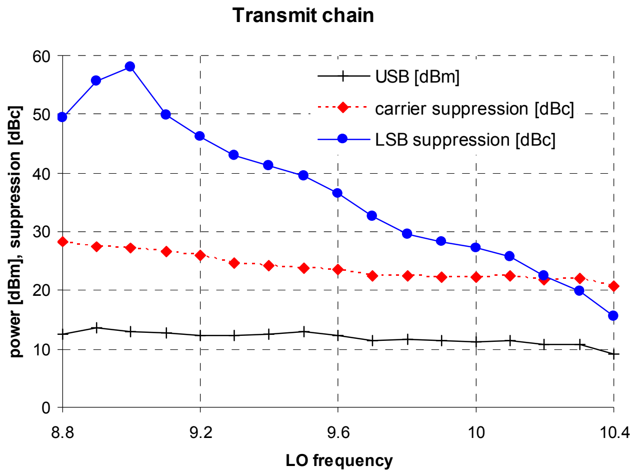

Fig. 5 Transmit chain measurement. Output power and suppression of unwanted products. The DDS frequency is 20 MHz, upper side band selected.

The suppression of the single sideband mixer is frequency dependent (Fig. 5). The LO from the motherboard has been swept and the spectrum measured to characterise the mixer in the transmit chain. The set-up is identical in the receive chain. Higher in the band the suppression decreases but up to 10 GHz the sideband suppression is better than 25 dBc and carrier suppression is better than 20 dBc over the whole band.

The noise figure over the band 0-10 MHz IF is 15 dB and the gain is 25 dB from the antenna port to a single I or Q output (Fig. 6).

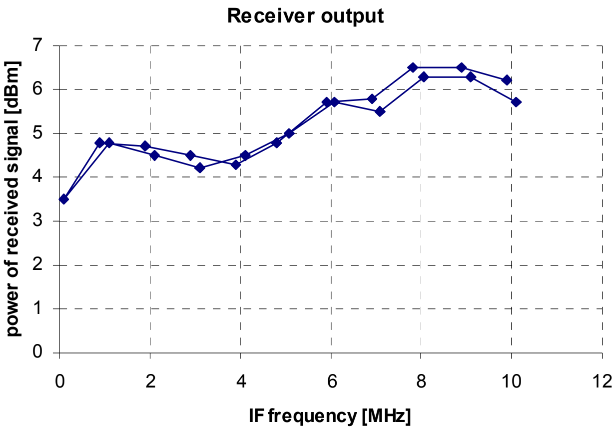

Fig. 6 Receiver gain measurement. Input signal at antenna port of -20 dBm.

VI. Demonstration Set-up

The radar system has an internal calibration loop. This will be used to align all wavefronts of the individual antennas. The system can be controlled from a standard PC (Fig. 7). For data acquisition an analogue-digital converter card is used. Either a single channel card can be used on the IF summed output. This allows for limited functionality: beam steering is done by properly setting the DDS phase of each TR module. With an eight channel acquisition system the full potential of digital beam forming on receive will be demonstrated. The system will be made demonstrable for indoor use during the conference poster session. The set-up can show position and velocity (range-doppler plots) and scan the beam in one plane.

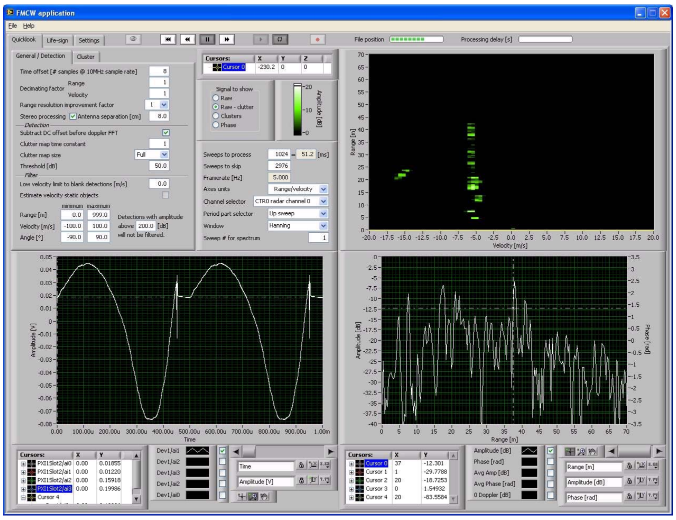

Fig. 7 Screenshot of the FMCW radar data processing and display GUI.

The system can be equipped with the TR modules described, based on COTS components. But also a set of TR modules is available with all RF components (Fig. 2, except DDS and splitter) integrated. This FMCW MMIC (Fig. 8) has been designed at TNO in a parallel project. It has been fabricated in a 0.25 µm SiGe BiCMOS process.

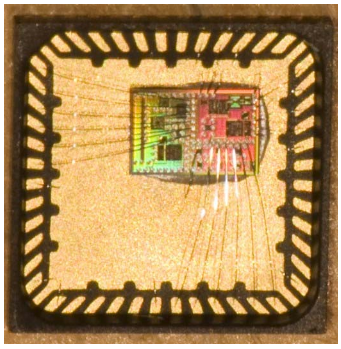

Fig. 8 FMCW MMIC in SiGe process mounted in a QFN package.

VII. Conclusions

An FMCW array radar has been designed and built from all COTS components. The LO and swept frequency signals are generated using Direct Digital Synthesisers. The effective isotropically radiated power for the eight element array is over 2 W, the noise figure of the receiver is 15 dB. A low-cost radar has been obtained for short range applications that is completely scalable to larger linear arrays. The radar will be demonstrated in the live poster sessions.

VIII. References

[1] C.M. Lievers, W.L. van Rossum, A.P.M. Maas, A.G. Huizing, *"Digital beam forming on transmit and receive with an AESA FMCW radar"*, proceedings of 4th European Radar Conference 2007, p. 47.

[2] R.J. Mailloux, *"Phased-Array Antenna Handbook",* 2nd ed. Artech House 2005.