SiGe:BiCMOS technology is enabling D-band link with Active Phased Antenna Array

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***Abstract*— While 5G wireless network is being currently deployed around the world, preliminary research activity has begun to look beyond 5G and conceptualize 6G standard. Although it is envisioned that 6G may bring an unprecedented transformation of the wireless network, in comparison with previous generations, from analog and RF point of view the need to address new frequency spectrum to increase achievable data rate and its implication on the development of differentiated More-than-Moore silicon technologies will remain. This paper reviews the exploitation, in the framework of the Horizon 2020 DREAM project, of the radio spectrum in D-band (130-174.4GHz), relying on power efficient silicon-based BiCMOS FEM transceiver and active phased antenna array with beam steering functionality, demonstrating wireless links with data rate exceeding current V-band and E-band wireless backhaul solutions.**

Keywords*— *mmW, THz, FEM, SiGe, BiCMOS, 5G, 6G

I. Introduction

The never-ending demand for increasing the mobile data transfer pushes wireless technology to increase achievable data rate, improve energy efficiency and provide ubiquitous low latency always-on broadband network coverage. To address this challenge, the 5G technology under deployment relies on two key concepts: (1) the transformation of modern communication network towards software-based virtual networks and (2) the use of new frequency bands.

It is anticipated that 6G networks will be more complex and more heterogenous [1]. Therefore, improving the current software-based virtual network concept developed for 5G may not be enough. Artificial Intelligence (AI) is foreseen as the key feature [2] to enable fast learning and adaption, paving the way for more versatile 6G systems. This trend should fuel the development of advanced CMOS nodes for digital integrated circuit (IC) design for power efficient AI-based ICs.

Looking at the RF spectrum, the 5G network access side is exploiting the spectrum below 6 GHz and frequency windows around 28 GHz and 39 GHz [3], while the E-band (71 GHz – 86 GHz) is going to cover the backhauling side. Current 6G preliminary investigations are focusing on mmW spectrum higher than 90 GHz [4]. To illustrate this point, United State has facilitated the experiments in the 95 GHz to 3 THz spectrum over the next decade [5] and the 275 GHz – 325 GHz band is attracting some attention [6], enabling the widest available bandwidths. All those envisaged frequency intervals will impose specific requirements on the RF system and consequent implications on the silicon-based differentiated technologies, supporting the development of associated highly integrated ICs and Systems on Chip (SoC). This is especially true for SiGe BiCMOS technology that support many ICs used in cellular systems and this is the focus of this paper.

In Section II we will review 5G and beyond applications and propose a technology partitioning. Section III is focused on BiCMOS technologies, giving an overview of current offer, and discussing future evolution. Finally, in section IV, we will share some results from BiCMOS application in the DREAM (*D-band Radio solution Enabling up to 100 Gbps reconfigurable Approach for Meshed beyond 5G networks*) project, drawing conclusions and perspectives.

II. 5G and Beyond Applications And Technology Positioning

A global overview of 5G and beyond network architectures is presented in Fig.1. The cellular networks have two distinct parts which impact on the selection of the differentiated silicon technologies: the infrastructure and the user terminal.

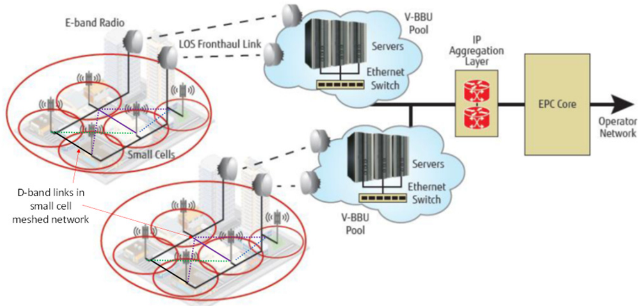

Fig. 1 C-RAN network with small cell meshed network by D-band links.

The infrastructure comprises the radio access, the backhauling, and the core networks, where the silicon chips enable the functionality of the following sub-systems:

- RF and mmW analog Front-End Modules (FEM), with low noise amplifier (LNA), power amplifier (PA) and switch, in massive MIMO (multiple-inputs-multiple-outputs) antennas and in multiband point to point radios;

- High speed optical modules.

From the user terminal side, the main challenge concerns the increasing complexity of the FEM to support new frequency bands. Due to the size and cost constraints of the current and the next generation commercial smartphones, to meet the best performances/cost trade-off, the silicon technology of choice addresses the frequency spectrum of the specific standard of connectivity:

- below 6 GHz for 5G;
- mmW for 5G and 6G;
- WiFi (specifically in the 6 GHz – 7 GHz band)

Once identified the network part being targeted, and from which the device specifications derive, we can then position differentiated silicon technologies on each target application to choose the most appropriate IC process. For clarity, differentiated technologies here considered, are just those with higher level of industrial maturity (excluding CMOS node below 28nm) optimized for analog and RF application or offering unique features with key devices, for example SiGe HBT (Heterojunction Bipolar Transistor). This paper focuses the ST's advanced SiGe:BiCMOS process as the RF IC semiconductor technology of choice for the full exploitation of the spectrum potential, notably above 90 GHz, bringing wireless systems to the speed of optical fibre technologies in future reconfigurable back hauling of small cell meshed networks. Addressing the ICT-09-2017 topic of the European Horizon 2020 Framework Programme, the DREAM project, through the exploitation of the radio spectrum in D-band with beam steering functionality, enables wireless links with data rate exceeding current V-band (57–67 GHz) and E-band (71–86 GHz) wireless backhaul solutions by at least a factor of 10 and brings wireless systems to the speed of optical systems.

III. BiCMOS Technologies

The short millimetre waves are the frequencies between 100 to 300 GHz. One of the motivations of exploiting this range is the huge frequency spectrum available, while the atmospheric and rain attenuation are relatively low. In addition, the standardization groups are starting to address the W- (92–114.25 GHz) and the D-band for channel arrangement in point-to-point fixed service links to introduce new essential parameters covering both antenna and equipment, allowing multi-gigabit wireless communication. Looking at Fig. 2,

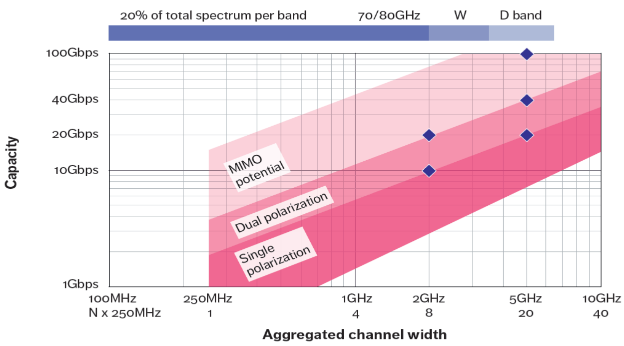

Fig. 2 Capacity vs channel bandwidth [8]

wider channels get higher capacities, but National spectrum Administrations commonly limit the maximum allowed channel size to secure a fair division among different users. The maximum channel size is typically limited to about 10 percent of the total band, as for E-band, where the maximum aggregated channel width is of 2 GHz. For the higher part of the millimetre wave spectrum, a greater possibility of frequency reuse is more feasible, so channels of up to about 20 percent of the total band may be allowed, as for D-band, where a channel size of 5 GHz (20 x 250 MHz) could be envisaged. In Figure 2 a 5 GHz width channel can support 20, 40 Gbps and even 100 Gbps in the longer term, although LO phase noise and other impairments, causing signal distortion, might limit the maximum modulation order for very wide channels. Furthermore, high spectral efficiencies, in wider channel bandwidths, imply very challenging specifications on the digital conversion side. The main system parameter to maximize the Key Performance Indicators (KPI) assessing the wireless link capacity over the hop length is the gross system gain (SG) in dB, which is related to the RF power amplifier output power, by the following relation:

$$SG|_{dB} = P_{out} + G_{TX\ antenna\ gain} + G_{RX\ antenna\ gain} - S_{vRX}$$

where S_{vRX} is the receiver front-end sensitivity in dBm. Then the main system component features impacting on the system gain and on which the transceiver designers can act, are:

1. transmitter and receiver antenna gain;
2. transmitter output power P_{out} in dBm;
3. receiver noise figure.

In all the three sub-system characteristics listed above, the proper semiconductor technology platform of choice determines the KPI requirement satisfaction in term of:

- gain, $G = 20\log_{10}(M\,N)$, where higher is the integration capability of the transceiver IC, higher is the M x N antenna elements in the Active Phased Antenna Array;
- transmitter RF output power versus frequency, which has been plotted for different technologies in Fig. 3;
- noise figure, as related to the receiver sensitivity, plotted versus frequency, for different technologies in Fig. 4.

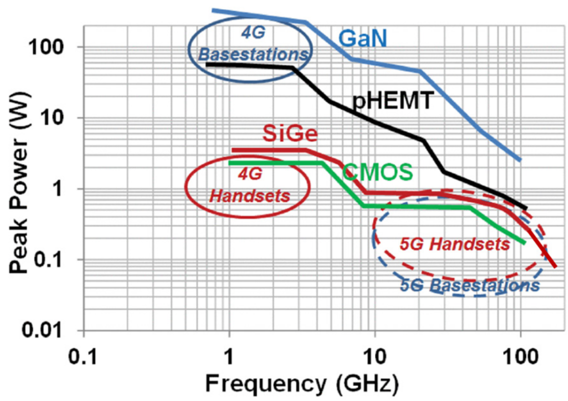

Fig. 3 Estimated power ranges for 5G mm-wave PAs and estimated maximum power for various technologies.

SiGe:C HBT based BiCMOS technologies, mainly addressing the automotive radar market, have gained increasing interest for emerging mmWave markets, as f_T and f_{MAX} of the HBT devices has exceeded the 200 GHz. The performance of SiGe HBT is no longer the limiting factor for a mmWave transceiver front end integration for small-cell applications with limited output power, but rather the quality factor of the on-chip passive devices, such as inductors, capacitors, and transmission lines for matching and tuning and their accurate characterization in the mmWave frequency domain.

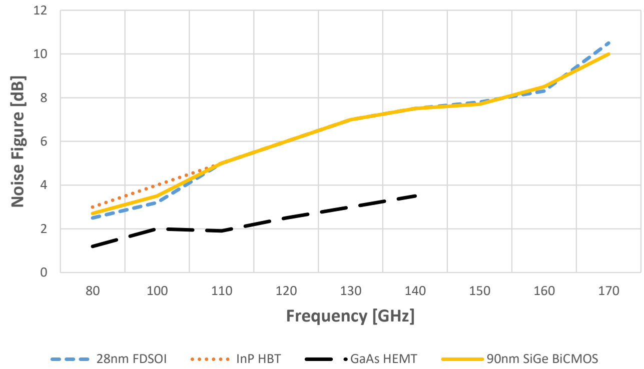

Fig. 4 The receiver noise figures, determining receiver sensitivity, versus frequency, for different technologies.

The combination of:

- the high frequency performance of the bipolar transistors, providing the high speed and gain that are critical for the high-frequency analog sections;
- the CMOS technology excellent for building moderately complex low-power logic functions;
- The 9 metals BEOL including the 2 upper layers with thicker copper for improved quality factor at mmWave of the passive devices (inductor, capacitors and transmission lines);

makes the SiGe:BiCMOS a process technology optimized for mixed-signal high frequency IC chip sets, for applications in cellular network mmWave backhauling, front hauling, satellite communication and radar.

STMicroelectronics develops SiGe BiCMOS technologies for more than 20 years, starting with 0.35-µm CMOS node, and offers today the most advanced BiCMOS technology in production in 55-nm. The move to more advanced CMOS nodes is feasible, with pros and cons for SiGe HBT performances, but no volume market is foreseen today. Therefore, current developments remain in 55-nm, which digital density and MOS analog & RF performances meets customer's requirements (moderately complex low-power logic functions). On the contrary, there is a strong push to continuously improve SiGe HBT performances to provide the high speed and gain that are critical for the high-frequency analog sections. A first significant step has been done evolving from BiCMOS9MW to BiCMOS055, with about +100 GHz invrease on both the unity gain frequencies of current (f_T) and power (f_{MAX}), to reach f_T > 300 GHz and f_{MAX} close to 400 GHz, while keeping the same transistor architecture. Further improving f_{MAX} requires to move to a new generation of architecture featuring an epitaxial intrinsic-to-extrinsic base link. Such an architecture is being developed in the new envisaged process, named BiCMOS055X, to target 400 GHz f_T and 600 GHz f_{MAX}, which is mandatory for 6G. SiGe HBTs with lower f_T are also available, when larger breakdown voltages (BVCEO) are required. RF switch devices are also being developed in BiCMOS9MW. Although listing the process features makes a suitable marketing introduction, the approach here is to present, by showing the RF IC test measurement results as well as the preliminary outcomes of a beyond 5G active phased array antenna system (APAAS) application demonstrator, the real extracted potentialities of a SiGe:BiCMOS based D-band analog front end chip set.

IV. Horizon 2020 DREAM Project

A. DREAM architecture

The DREAM project vision and objectives rely on power efficient silicon based BiCMOS transceiver analog front end operating in D-band and enabling cost efficient mass-production. A beam steering integrated antenna array using an intelligent low-cost packaging technology will provide a prototype for the implementation of the beyond 5G network proof of concept in realistic environment.

The DREAM transceiver architecture with 4x4 TX antenna array and 4x4 RX antenna array is shown in Fig. 5.

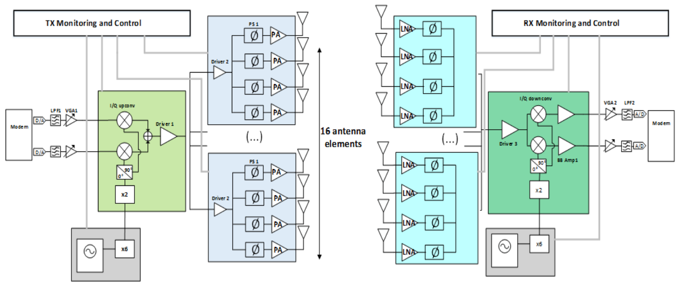

Fig. 5 transceiver architecture with 4 TX antenna array and 4 RX antenna array

The digital bit stream outputted from the Modem, which implements the proper modulation order function is converted by the two digital-to-analog-converter (DAC) in the in-phase (I) and the quadrature-phase (Q) components of the message analog modulating signal. The baseband signal is directly mixed with the local oscillator carrier frequency (VCO) by the quadrature mixer to get the up-conversion to the modulated carrier in the D-band frequency range around 150 GHz. The up-converted RF signal is then amplified, divided, and distributed to the active antenna array system. A single satellite IC drives 4 antenna array elements, each by phase shifting and power amplifying the modulated carrier frequency in D-band. The wireless signal at a carrier frequency within the D-band frequency range, is received by the active antenna array, where 4 antenna array elements feed one satellite IC, which includes 4 correspondent LNAs and phase shifters. The signal from the satellite ICs is then combined and down converted by the quadrature mixing process with the local oscillator (LO) frequency in D-band. The so obtained analog baseband signal is amplified by the variable gain amplifier (VGA), which adjusts the signal dynamic to the proper level compatible with the optimal analog-to-digital converter (ADC) input signal level specification. The digital bit stream got by the ADC, is then sent to the Modem, which implements the digital demodulation function.

B. SiGe:BiCMOS test chips

BiCMOS technology appears as the most appropriate choice for the antenna phased array-based infrastructure market, as the device parameters address properly the mmWave RF IC requirements, though, due to the cost constraint implied by mMIMO implementations, the RF SOI technology is getting traction on this market side. RF SOI technology is today most appropriate to address user terminal market since it enables cost effective and high performances LNA and switch. However, BiCMOS technology is gaining increasing interest on the WiFi connectivity market, especially with the recent introduction of WiFi6. D-band signal amplifiers have been designed and fabricated in ST's BiCMOS 55nm gate length process. Fig. 6 shows the amplifier test die micro photo and the simulated and experimental characterization in term of both small S-parameters and large RF-power signal of several amplifiers. The constraints of distance between elementary antennas and the use of one PA per antenna to increase the total transmitted power, led us to successfully develop and integrate wideband single-ended D-band amplifiers for VGAs, PAs and LNAs in large chip. Also, a D-band power detector functionality has been designed, characterized, and shown in the same figure.

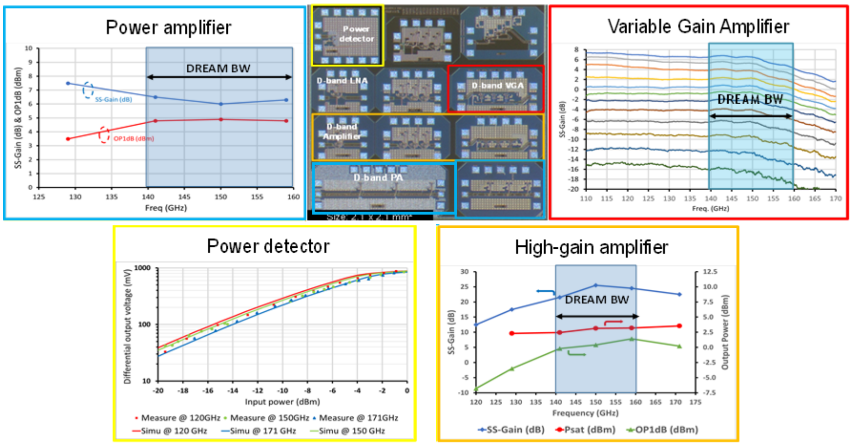

Fig. 6 DREAM's test chips: Amplifiers test chip and functional characterization measurements

The Fig. 7 gets a comprehensive view of the performances of the 2 test chips related to the D-band I/Q modulator and demodulator analog FEM transceiver.

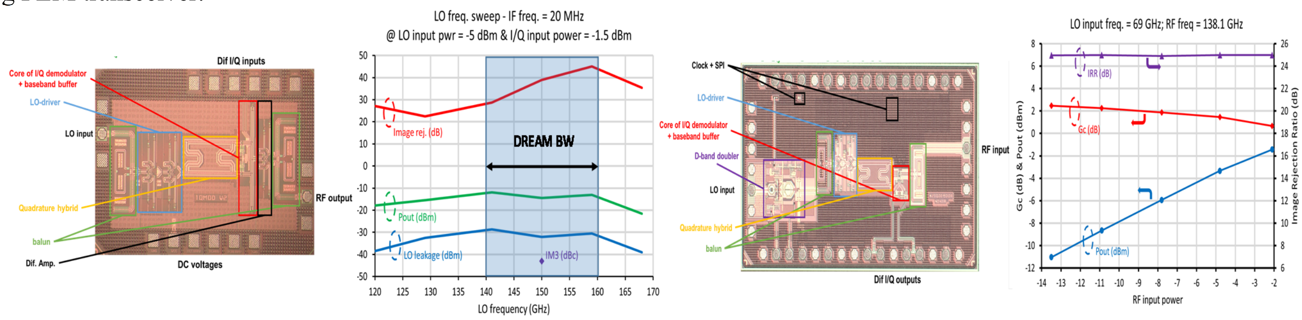

Fig. 7 DREAM's direct I/Q converters in D-band: modulator on the left and demodulator on the right.

The TX modulator chip is fed by the baseband I/Q signals from the modem and the LO from a frequency multiplier by 6 and produces at its output the D-band signal to be transmitted. It consists of a quadrature upconverter, a 90-degree differential branchline to produce quadrature LO signals from a differential LO input, a frequency doubler, with its own input buffer and a RF buffer get the targeted conversion gain. It also includes a SPI slave to communicate with the monitor and control block and configure different parameters of the upconverter and a I/Q differential amplifier to adapt the signals from the modem to the modulator inputs. The RX demodulator chip gets the RF signal from the RX antenna driver and the LO signal from the multiplier by 6 to deliver the I/Q baseband signals. The chip includes the last frequency doubler in D-band, with its own input buffer. It also includes an SPI slave to communicate with the monitor and control block and configure various converter parameters. On both direct converters, the performances obtained in terms of image rejection, LO to RF leakage and linearity will enable the validation of the system for high modulation schemes. Thanks to the accuracy of ST's design kit, which includes description files for the parasitic extractions and electromagnetic simulations which allowed to get these performances in D-band.

During the DREAM project timeframe, several test chips of key building blocks for phased-array D-band transmitter and receiver have been designed. Operating at D-Band enables designing antenna phased-arrays with a compact size and form factor. Minimizing the occupied area in D-band antenna phased arrays by integrating on the same die, the RF front end analog functionalities and the digital control and monitoring interfaces is a further enabling feature of an IC technology platform [9]. Fig. 8 (left) shows the die micro photo of a 140–160 GHz vector-modulator type phase shifter, integrated in ST's 55 nm BiCMOS technology, which is deeply described in [10].

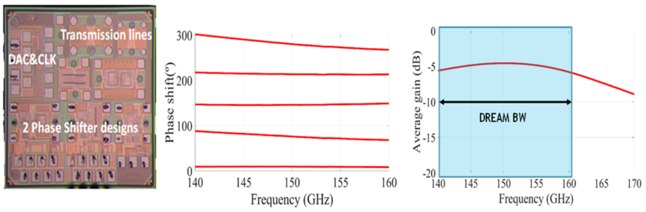

Fig. 8 DREAM's test chips: D-band phase shifter and measurements

Measured insertion losses are on the right, while a complete continuous 360° phase shifting versus frequency has been tested and is reported on the centre.

A frequency multiplier by 6 has been designed and fabricated in ST's BiCMOS55nm technology. It converts the input X-band signal to E-band, firstly by a tripler, whose novel architecture has been patented, followed by a doubler. The bias current for each bock and some other fine-tuning parameters are digitally programmable through the serial peripheral interface (SPI). Multiplication by 2, up to the D-band, is realised by using two parallel devices in push-push configuration. Although the push-push pair already generates the second harmonic of the input signal, it still needs amplification to drive the load with sufficient power. In Fig. 9, the main measurements parameters of both the multiplier test chips are reported.

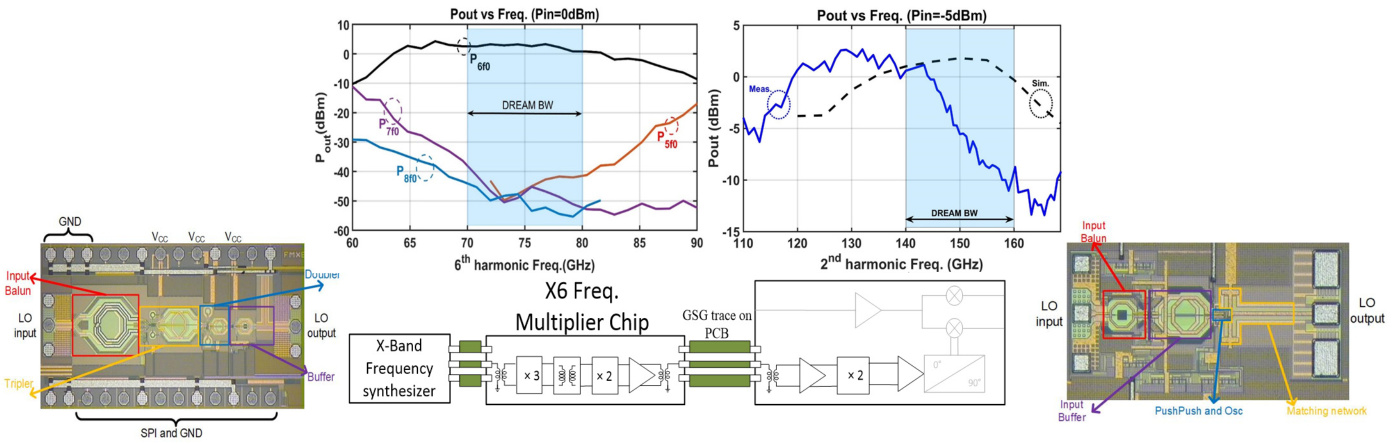

Fig. 9 DREAM's test chips: frequency multipliers

C. *Active antenna array*

Several beam-steering architectures have been studied, such as phased antenna arrays. These systems can boost the transmitter Equivalent, Isotropically Radiated Power (EIRP) and enhance the receiver noise figure by exploiting spatial combining. The developed antenna array concepts in this project will advance the state of the art in D-band systems. The fully integrated phase-shifters, for D-band active phased antenna array system, fabricated in SiGe:BiCMOS technology is a clear progress for these kinds of devices and enable their feasibility at the lower cost implementation. Currently there are not any commercially available phase shifters operating in the D-band frequency range. A vector-modulator type phase shifter has been implemented, die photo in Fig. 8, which allows independent control of the output amplitude and phase with very high resolution. The 8-metals stack of the ST's BiCMOS process, including the top thick copper metal layer, has enabled the feasibility of the most critical parts of the phase shifter, such as the output balun and the passive quadrature coupler, which has been optimized in term of size, aspect ratio and signal losses [10]. The outcomes of this project include a high gain beam steering active antenna array for use in backhauling radio links. The active antenna array features tight integration of the antennas and RFICs for maximum performance. These have been developed and co-simulated together with the antenna array elements for maximum performance. The schematic description of the 4x4 active antenna array is shown in Fig. 10.

The antenna array is realized on multilayer high frequency PCBs [11]. Both studied substrate materials (Astra MT77 and Megtron 7N) have demonstrated their applicability for D-band [12, 13].

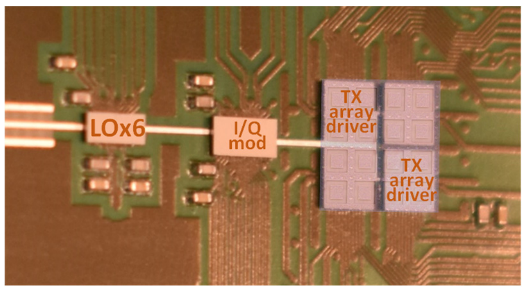

Fig. 10 DREAM's 4x4 TX active antenna array system (top view). Antenna array substrate bottom view has been made visible in transparency mode. Similar picture is for the 4x4 RX active antenna array system.

The targeted operating frequency range for the complete antenna array is 140–160 GHz. The 20 GHz bandwidth around 150 GHz is about 14% and necessitates the use of wideband antenna elements and chip-to-PCB transitions. The cavity-backed aperture-coupled patch antenna (ACPA) is chosen as antenna topology. The ACPA enables independent optimization of the feed circuitry and the antenna operation. The ground plane isolates the feed line network and the active components from the radiators, and spurious radiation is reduced [11].

The main advantages of beam steering are the possibility of mesh networking, reconfigurability, and compensation of mast swaying for low-cost base station deployment.

D. D-band link demonstrator test bench

The approach that will be used here for testing and validation of the transceiver and the demonstrator is based on over-the-air (OTA) measurements instead of the more common method based on conducted measurements.

The preliminary set-up of the test bench is necessary for reaching reliable measurements. For this reason, some basic parameters of the test bench will be defined at the latest stage of the work only, after the transceivers preliminary calibration phase will be concluded.

The main parameter that must be defined is the collocation distance (Cd) between two transceivers. This distance, here acting as the hop length of the link, shall be considered here as a fundamental parameter of the test bench, since it will play the role of the attenuator when conducted measurements are concerned. In Fig. 11 the photo of the preliminary D-band link test bench.

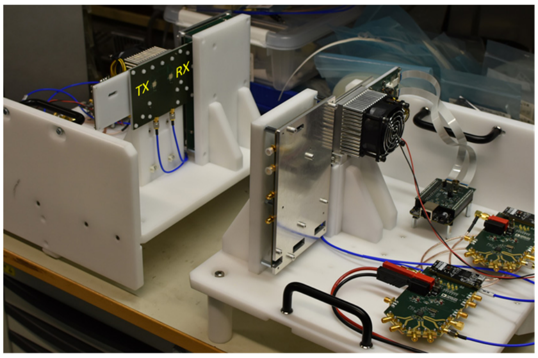

Fig. 11 DREAM's demo test bench of the D-band link lab trial.

Preliminary results from the demonstrator test bench are very encouraging. The following picture shown the demonstrator set-up, on the left, and the very preliminary result of beam steering measurements on the right, taken from the receiver antenna. Substantially a +/-40° of steering angle has been obtained and considering that the antenna array elements coefficients have not yet been tuned, the antenna response appears very promising as shown in Fig. 12.

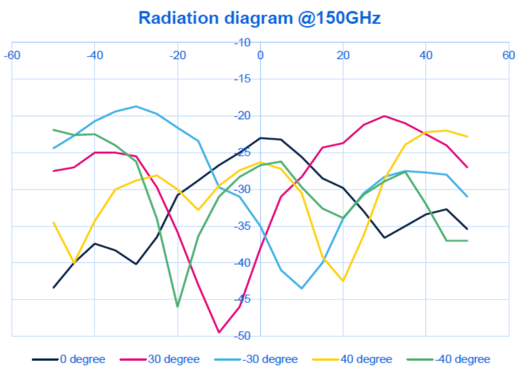

Fig. 12 D-band preliminary antenna beam steering results.

CONCLUSION

The ST's advanced SiGe:BiCMOS technology named BICMOS055 has been proved as a viable and enabling technology for beyond 100 GHz mmWave front end modules, by fully exploiting the increased flexibility envisioned by the mixing digital and analog functionalities. Additionally, low to medium complexity digital circuits for an active phased antenna array can be realized in the same process.

ACKNOWLEDGMENT

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Horizon 2020 DRAGON project, just started in December 2020, is reaping the R&D effort fruits to optimize the IC designs in view of the higher integration levels required by a 32x32 active antenna array, the power consumption reduction, and the mass production.

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