D5.3

Final Evaluation of the Telecom Prototype

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Abstract:	This deliverable reports the assembly of the D-band front-end modules and the test results of the final demonstrator.
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Disclaimer

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Executive Summary

Deliverable 5.3 describes the development of the final telecom prototype and reports its measured performance based on the test carried out at module, radio and link level.

All components necessary for assembling D-band front-end modules were delivered by end of September 2018. Four complete modules were first assembled and tested. Unfortunately, none of them worked properly. While debugging was carried out to identify the root-cause, two other tracks were taking in parallel: 1) reparation of the four fault modules; and 2) assembling additional modules. Now both tracks have turned out to be successful and lead to positive measured results.

In brief, a pair of Tx and Rx modules were tested and found working. Data transport using 16-QAM and 32-QAM modulated signals is demonstrated in test setup using both waveguide interface and antennas (over-the-air). Measurement of the modules and link is still ongoing and will continue. Further detailed characterization will be pursued in the coming months to measure, for instance, the receiver sensitivity, the system gain and the maximum data-rate the prototype can support.

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Chapter 1 Introduction

The concrete business and lead application case in M3TERA is a microsystem for point-to-point wireless links featuring compact size, low cost and high capacity in frequency space between 110 GHz to 170 GHz, the D-band. As the end-user, Ericsson has been driving the development of the primary prototype to assess the platform and the key technology elements developed in M3TERA.

In this report, we first describe briefly the assembly of the D-band front-end modules (including the problem we encountered and the measures we took). Then radio and link performance are presented based on the test results of the first pair of working modules. The measurement is ongoing and will continue in the coming months until the SiGe D-band link based on M3TERA hardware platform is fully characterized.

Chapter 2 Assembly of the D-band modules

2.1 Components

Although delayed, all components that are necessary for assembling D-band modules were delivered to Ericsson Borås by September 25th. The key components are listed in Table 1.

Components	Function	Deliveryed by
SiGe MMIC	Tx and Rx chipset	Chalmers
Si Platform	platform for interconnect and package	KTH
SiC	Fan-out for RF routing	Chalmers
PCB	DC bias & RF conentors	Chalmers
Metal fixture	Transition between the platform and external antenna	Ericsson
Antena	Over-the-air (OTA) transimission	Anteral
Mechanics	House for all aprts	Ericsson
Chip capacitors	to stableize the circuits operation	Ericsson
RF connector	I/O for IF and LO signal	Ericsson
SMT resistor and capacitor	to stabalize the circuits operation	Chalmers

Table 1: The components necessary for D-band module assembly

The design of the metal fixture for the transition between the platform and external antenna has resulted in a patent application by Ericsson, filed in April 2018 [1]. A manuscript is under drafting to publish the transition idea which is experimentally proven to deliver wideband and low loss.

2.2 Assembly of the first four modules

Automatic assembly was carried out at Ericsson Borås. Four D-band modules were first assembled and wire-bonded by October 18th and were delivered to Ericsson Lindholmen for testing.

Figure 1 is a photo showing a Tx MMIC assembled and wire-bonded to a MEMS chip (the Platform) which is assembled on a metal fixture. The MMIC is partially inserted into the micromachined waveguide and is wire-bonded as well with a SiC board. What can be seen further, are two chip capacitors on the right used for RF by-pass (grounding) to stabilize the circuit operation.

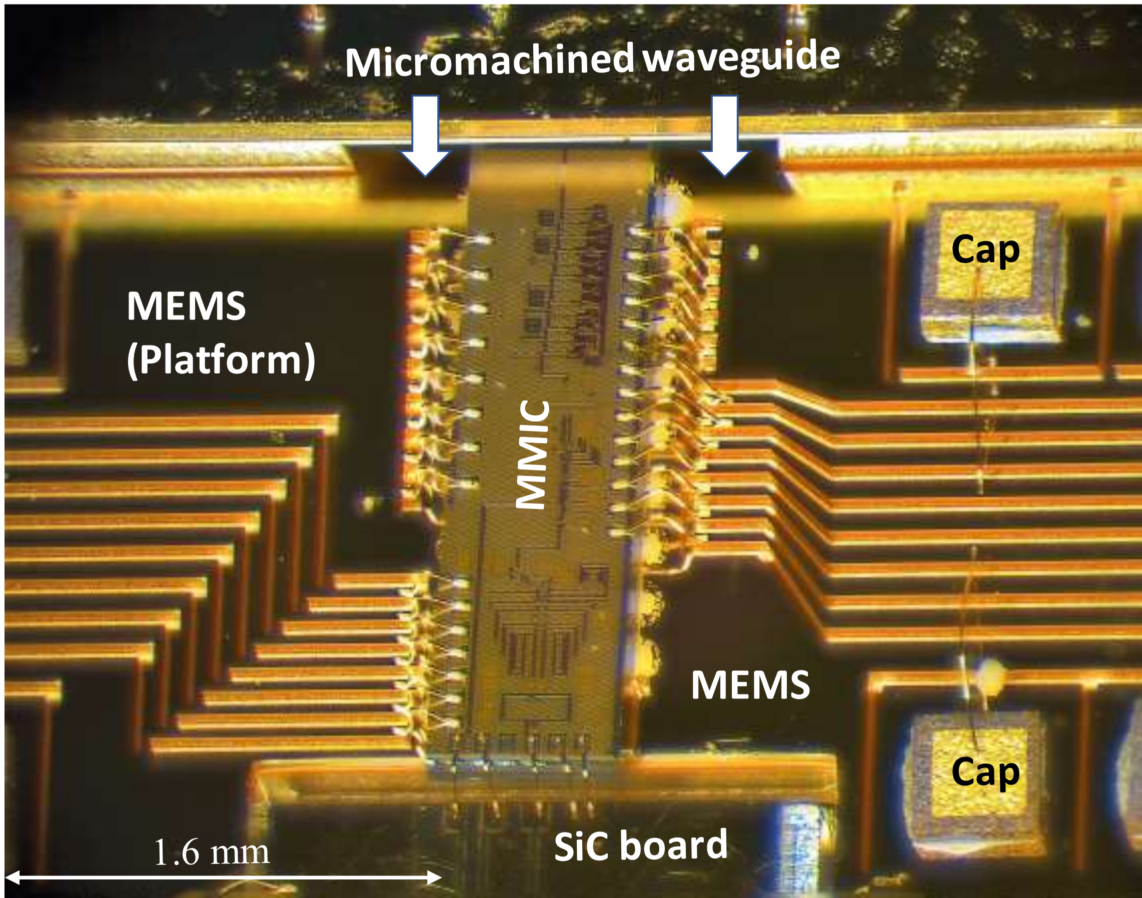

Figure 1: An assembled platform and a MMIC wire-bonded to the platform. The MMIC is inserted partially into the micromachined waveguide and wire-bonded as well with a SiC board

Figure 2 is a photo showing a Tx SiC board assembled to a fixture and wire-bonded with a MMIC, the MEMS platform and the PCB.

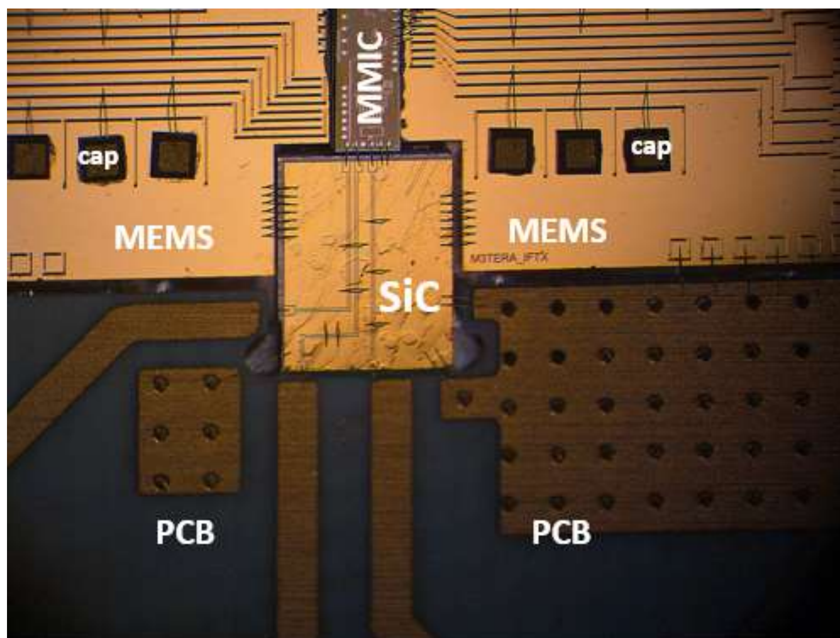

Figure 2: A SiC board assembled to a fixture and wire-bonded with a MMIC, the platform and a PCB.

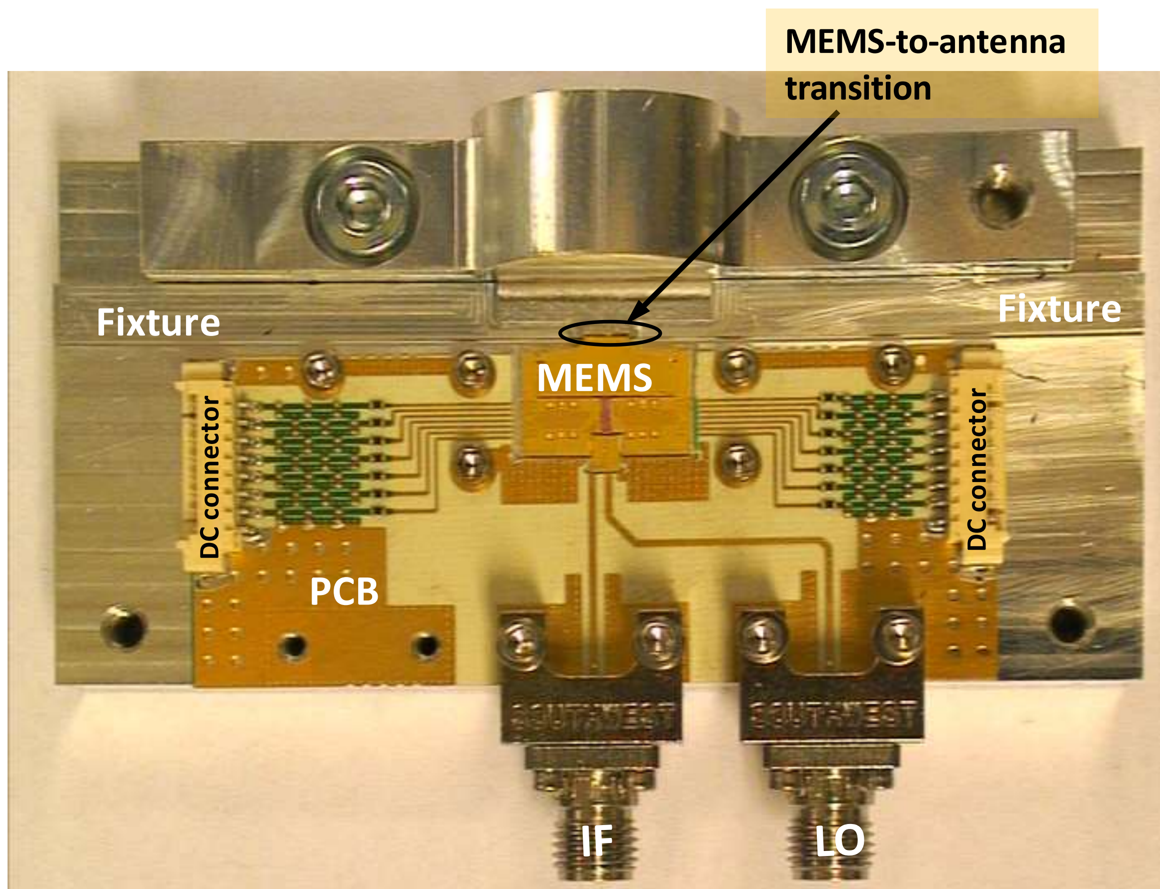

Figure 3: A complete D-band module after assembly and wire-bond

Figure 3 is a photo of a completely assembled Rx module containing the metal fixture, the MEMS-to-metal waveguide transition, the MEMS platform, the MMIC, the SiC and the PCB, in addition to passive components such as capacitors, resistors, DC and RF connectors.

Unfortunately, none of the four modules worked properly. For one Tx module, Tx1, DC current and voltage for were measured and were more-or-less as expected, but no RF output power could be detected. The remaining three modules, Tx2, Rx1 and Rx2, did not behave properly at all DC-wise. Most common in our observation is that one or more biases behaved like they had a low-ohmic resistance to electric ground, i.e., applying a small DC voltage resulted in a large current.

2.3 Assembly of second set of modules

During an emergency meeting held among Ericsson Lindholmen, Ericsson Borås, Chalmers KTH, three tracks were identified to follow as the way forward:

- Track #1: Debug the problem to find the failure root-causes
- Track #2: Repair the existing 4 modules
- Track #3: Assembly addition new modules

For Track #1, two reasons were considered as the most likely root-causes. To verify this, the bonding wires to the DC lines on the MEMS platform were removed. Then the DC lines were

measured and, indeed, some of the DC lines did behave similarly as when the wires were bonded. This confirms that the DC lines are at least one root-cause.

The second most likely root-cause is related to the automatic bonding machine, the bonder. Due to its specific construction, the bonder may release electrical pulses at the wedge head and potentially damage the transistors in the MMIC. To verify this, Ericsson investigated the two bonders at Borås, involving two Ericsson experts in the field. Shown in Figure 4 are two screenshots from the oscilloscope. As can be seen, pulses do appear about every 20 µs and the peaks can be 4-volt high.

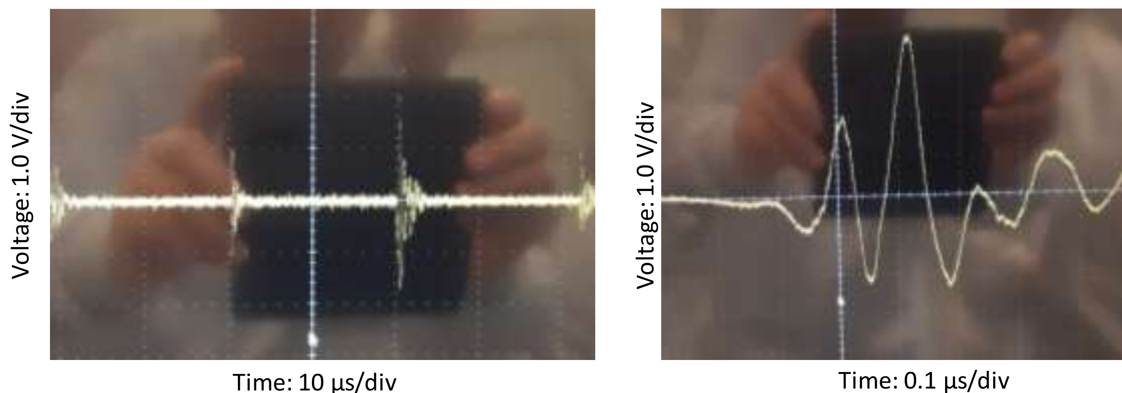

Figure 4: The pulses observed at the wedge head of the bonder, using a differential probe and an oscilloscope. The left is a zoomed-in photo.

To be sure that these pulses do damage the MMICs, two experiments were carried out, in two opposite ways:

1. The MMICs on the fault modules were de-assembled, then on-wafer tested using DC-probes. The measured DC current and voltage (I/V) showed no abnormal behavior for all biases
2. In an opposite way, two MMICs and two MEMS chips, all DC-normal, were wire-bonded at Borås in the same way as when the first 4 modules were bonded.

Neither of the experiments described above showed abnormal DC behavior, meaning that at least DC-wise the MMICs were not damaged during the wire-bonding.

Track #2, repairing the then-existing four fault modules: The bonding wires on the MMICs were removed and all MMICs were de-assembled from the MEMS platform. When the wires are removed, the MEMS DC lines were isolated from the MMICs and could be easily tested. Whenever a line was found to have DC problem, a positive voltage was applied, ranging from a few volts to 38V, to burn away the “short” or the low-ohmic contact. This method was recommended by KTH and was turned out to be efficient in dealing with the DC problem.

After the MEMS bias lines were cleaned, the MMICs were re-assembled and wire-bonded. Unlike the first time, all MMICs were DC-probed before their delivery. The effort along this track resulted in three modules: Rx2, Tx1 and Tx2 (Rx1 was found broken and was not repaired).

Track #3, making new modules: The major bottleneck for assembling new modules is the lack of additional MEMS chips. Fortunately, KTH found that some of their MEMS samples designed for other tests may be useful after cutting. The cutting resulted several samples. At least two them were believed to be fine and were used in the final assembly. After producing new SiC, PCBs and mechanics modification, two new modules were assembled in this track: Rx3 and Tx3.

Chapter 3 Test results up to end of November

3.1 Module test and measurement

Tested first was a new Tx module, Tx3, produced in Track #3 (see §2.3). When being powered up, its DC current and voltage behaved as expected. Its RF output power was measured with a D-band power meter and the results was plotted in Figure 5.

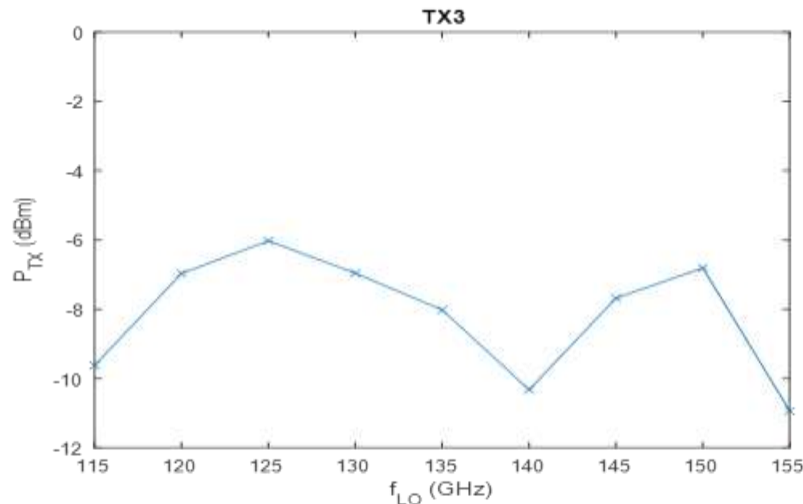

Figure 5: Measured output power vs LO frequency for Tx3 module (IF=1.5 GHz)

Output power of -6 dBm is obtained at 125 GHz. The dip around 140 GHz is believed due to the two transitions in the interconnect: i) the transition between MMIC and Si waveguide shows a similar dip; and ii) as the MEMS chip is obtained by dicing the original chip, the sidewall facing the metal waveguide does not have the deaired shape, which according to simulation causes a dip around 140 GHz. However, it has not been verified experimentally.

3.2 Link test (Continuous wave)

The Tx3 module is paired with Rx2 which is a repaired module. The pair were connected first through a D-band attenuator using metal waveguides. Test setup is shown in Figure 6. Continuous wave was used to see whether any IF signal might be detected at the receiver. Figure 7 shows the IF spectral measured at Rx2 when f_{LO}=145 GHz and f_{IF} =1.25 GHz. The large second IF harmonic is not expected and will be investigated later.

The same pair has been tested with OTA interface, using the two antennas Anteral developed in M3TERA. Similar results were obtained. However, careful calibration in the measurement is necessary for an accurate quantitative characterization of the link (radio + antenna), which we do not have time to carry out at the moment, unfortunately.

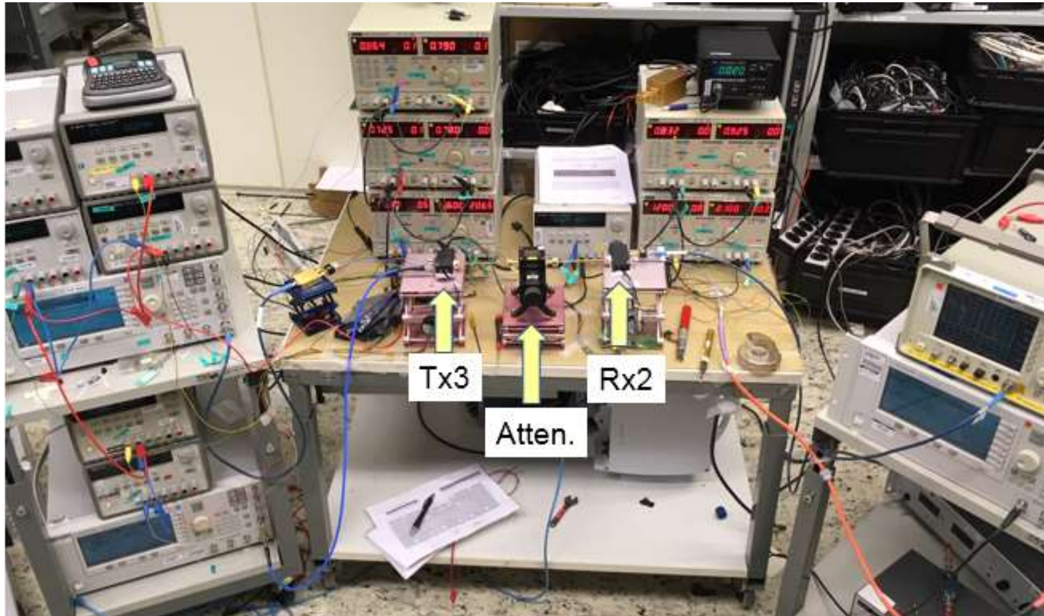

Figure 6: Test setup for the first link test. Tx3 and Rx2 are connected with a D-band attenuator

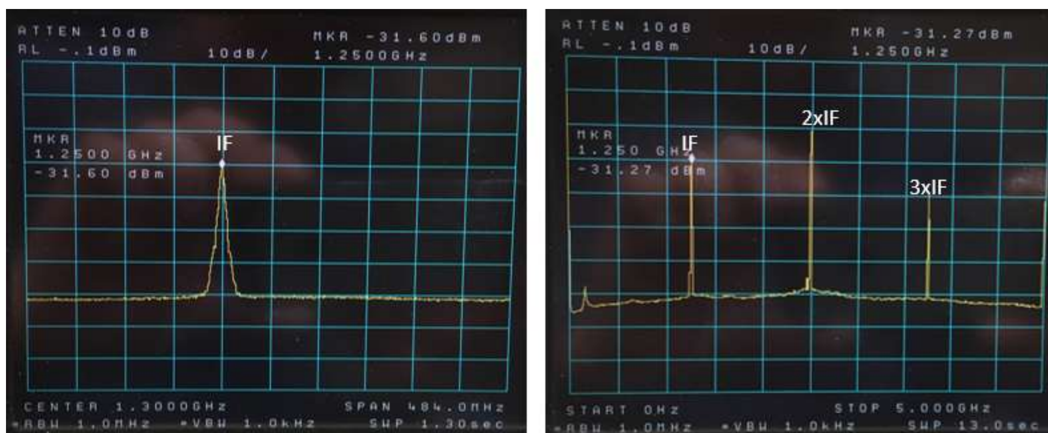

Figure 7: IF signal measured at Rx2 module, LO= 145 GHz, IF=1.25 GHz

3.3 Link test (modulated signal)

To further test the link, an arbitrary waveform generator was used as a source providing a modulated IF signal. A signal-and-spectrum analyzer was used to detect the data from the received IF. When QPSK modulation is used, the link worked, as shown in Figure 8. In this test, Anteral' s antennas were used with a separation of about 15 cm. Actually, the observed constellation diagram was not stable in this setup. One reason could be that two unsynchronized LO sources were used and there was no carrier recovery deployed in the detection. Therefore, in the following tests, a common LO source was shared by Tx and Rx. In addition, the air-interface (the antennas) was replaced by a D-band attenuator to easily control the input power to the receiver.

With these setup changes, the constellation diagram become stable. Higher order modulations such as 16 QAM and 32 QAM were also used in addition to QPSK. Figure 9 are screenshots of the constellation diagram for 16 QAM and 32 QAM observed for the Tx3-Rx2 link. The LO frequency is 131 GHz; the IF is 1.5 GHz and the attenuation is 12 dB on the attenuator.

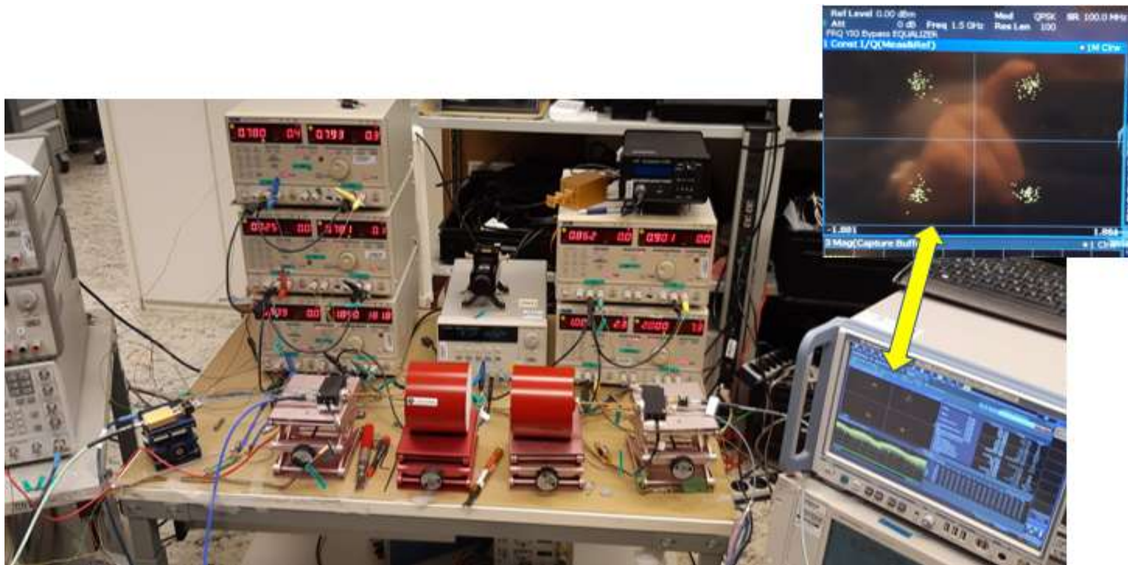

Figure 8 OTA link test using QPSK modulation

Figure 9: Screenshot of the constellation diagram for 16 QAM and 32 QAM observed for the Tx3-Rx2 link

Based on the symbol "clouds" seen on the constellation diagram, the link performance is quite good. Nevertheless, we have not measured the EVM or bit-error rate. These system performance parameters will be measured after all modules have been tested. By then a quantitative description of the link will be available.

To fully characterize the telecom prototype demonstrator, the following need to be carried out, which is in our plan:

- Link test using Ericsson's Modem and IF&LO generation boards
- Do rigorous calibration and measure the receiver sensitivity, thus, the system gain
- Based on above, measure the EVM and MSE, find out the highest capacity the prototype can support
- Understand the high 2nd IF harmonic and investigate its impact
- Develop radio mechanics to accommodate the SiGe modules
- Install outdoor link and perform link test (propagation, weather impact, distance, etc.)

Chapter 4 Conclusions

Although unexpected things happened at the last stage of this research project, the partners involved in development of the components and modules managed to produce additional modules though hardworking and excellent collaboration. Preliminary test and measurement show that these modules work fine. A millimeter-wave D-band radio link, based on the SiGe MMICs mounted on the micromachined silicon platform, has been successfully demonstrated using the antennas developed by M3TERA. Data transport over the link has been verified using QPSK, 16QAM and 32QAM. Now, it can be concluded that the interconnect and package solution based on the 3D micromachined technology works, even though a quantitative comparison with existing technologies requires a full characterization of the demonstrator from both, economical and technical perspective.

Chapter 5 List of Abbreviations

Abbreviation	Explanation
BB	baseband
CW	continuous wave
EVM	error vector magnitude
FE	front-end
IF	intermediate frequency
I/O	input/output
I/V	current and voltage
LO	local oscillator
MMIC	monolithic microwave integrated circuit
mmW	millimeter-wave
Modem	modulator and demodulator
MSE	mean square error
OTA	over-the-air
Rx	receiver
Tx	transmitter

Chapter 6 Bibliography

[1] Mikael Hörberg and Yinggang Li, “Waveguide interface and non-galvanic waveguide transition for microcircuits”, Ericsson patent application, P74583, filed April 18, 2018