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Terahertz end-to-end wireless systems supporting ultra-high data Rate applications

ThoR

Deliverable D4.3

300 GHz circuits validation

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Change register

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1. Statement of independence

The work described in this document is genuinely a result of efforts pertaining to the ThoR project. Any external source is properly referenced.

Confirmation by Authors:	Laurenz John	IAF
	Iulia Dan, Ingmar Kallfass	USTUTT

2. Abbreviations

Au	Gold
AWGN	Additive White Gaussian Noise
BB	Baseband
$BV_{off\text{-}state}$	off-state breakdown voltage
CS	common source
BW	Bandwidth
EVM	Error Vector Magnitude
FDD	Frequency Division Duplex
Gbps	Giga bits per second
GCPWG	Grounded coplanar waveguide
$g_{m,max}$	maximum transconductance
HEMT	high electron mobility transistor
IF	Intermediate Frequency
InGaAs	Indium Gallium Arsenide
LACP	Link Aggregation Control Protocol
LAG	Link Aggregation Protocol
LNA	Low Noise Amplifier
LO	Local Oscillator
mHEMT	metamorphic high electron mobility transistor
MIM	Metal-Insulator-Metal Capacitor
MMIC	millimeterwave monolithic integrated circuits
NF	Noise Figure
OMN	Output matching network

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P_{-1dB}	1 dB compression point
PA	Power Amplifier
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature phase shift keying
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuit
RX	Receiver
S/N	Signal to Noise ratio
SFP	Small Form-factor Pluggable
SSPA	Solid State Power Amplifier
TDD	Time Division Duplex
TFMSL	Thin-film microstrip line
TX	Transmitter
TWTA	Travelling Wave Tube Amplifier
V_{DS}	Drain Source Voltage
V_{GS}	Gate Source Voltage

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3. Executive summary

This deliverable reports on the on-wafer measurement results of the 300-GHz solid-state circuits developed in WP4. The measured performance of multiplier and amplifier test circuits as well as the fully integrated 300-GHz front-end and high-power amplifier MMICs is discussed and evaluated.

The functionality of the 300-GHz power amplifier circuits as well as the receiver and transmitter front-end MMICs is verified within the requirements for overall system implementation in the ThoR project, permitting the packaging into waveguide modules for system integration.

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4. Introduction

Within the ThoR project, the first superheterodyne architecture for high-data-rate wireless communication at THz frequencies is developed. One of the key building blocks of the ThoR point-to-point link are the 300-GHz solid-state front-ends, which enable the bit-transparent up and down conversion of real-time data, aggregated in the V- and E-band. The front-end MMICs are developed as a part of WP4, prior to the design and fabrication of the waveguide modules, in order to evaluate and ensure their functionality.

This deliverable describes the on-wafer measurement results of the 300-GHz receiver and transmitter MMICs, the 300-GHz high-power amplifier MMICs as well as some stand-alone multiplier and amplifier circuits, which were developed in T4.2. The designs are based on D2.3 Specification of RF Design [1], which addressed the design and architecture considerations for the 300-GHz transmitter, receiver and power amplifier implementations developed in WP2.

The design of the multiplier, mixing and amplifier circuits, which are required for the development of the fully integrated 300-GHz front-end MMICs, was reported in detail in D4.2 RF Circuits Design [2]. In the following sections, the on-wafer measured performance of those circuits is described and evaluated.

First, the measurement setups for the conducted small- and large-signal on-wafer measurements are described in Section 5. In Section 6 to Section 8, the measured performance of stand-alone multiplier and amplifier circuits as well as the fully integrated frond-end MMICs is discussed, followed by a summary in Section 9.

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5. Measurement setup

Depending on the respective circuit type, different measurement setups are required for the characterization of amplifiers, frequency multipliers or mixers, which can differ in the input/output frequency range of operation, required power level and number of ports. The on-wafer measurement setups, which have been used at Fraunhofer IAF to conduct the circuit characterization described in this document, are described in the following.

Small-Signal Amplifier Measurements
The on-wafer 200-335-GHz S-parameter measurements of low-noise and power amplifier circuits were done using an Agilent PNA system and VDI WR-3.4 extension modules. The entire setup was calibrated to the probe tip of the RF-probes by performing a thru-reflect-line (TRL) calibration, using an impedance standard substrate (ISS).

Large-Signal Amplifier Measurements
On-wafer scalar power measurements at H-band were done using in-house built frequency multiplier and amplifier modules to synthesize the input signal around 200 GHz to 330 GHz. The output power of the amplifier MMICs was measured using a VDI Erickson PM5 Power Meter. The whole setup was calibrated to the probe tip of the RF-probes, using an impedance standard substrate (ISS).

Multiplier Measurement Setup
The on-wafer measurements of frequency multipliers by three were conducted using a Keysight PSG frequency synthesizer with extension module and an in-house built amplifier module to synthesise the input signal with sufficient input power around 70 GHz. The output power of the third harmonic at H-band was measured using a VDI Ericson PM5 Power Meter. The system was calibrated on waveguide level and the known probe losses were deembedded.

Receiver Measurement Setup
The 300-GHz receiver MMICs were measured using in-house built frequency multiplier and amplifier modules to synthesize the 300-GHz RF input signal. The LO signal around 70 GHz was generated using the same source chain as for the multiplier measurements (synthesizer + amplifier module). The IF signal at W-band frequencies was measured using and Agilent PXA spectrum analyzer. Due to the lower cut-off frequency of the W-band waveguide, this measurement setup is limited to IF frequencies above 65 GHz. The system was calibrated on waveguide level and the known probe losses were deembedded.

Transmitter Measurement Setup
For the on-wafer measurement of the 300-GHz transmitter MMIC, the same 70-GHz LO source as for the receiver MMICs was used. The IF signal was generated using an HP 8360 frequency synthesizer with extension module, the IF frequency band was limited to frequencies above 70 GHz. The 300-GHz output power of the TX MMIC was measured using a VDI Ericson PM5 Power Meter. The system was calibrated on waveguide level and the known probe losses were deembedded.

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6. Measurement of 300 GHz Components

The RF system, as described in detail in WP4, D4.2 consists of a 300 GHz transmitter (TX), a solid state amplifier (SSPA) and a 300 GHz receiver (RX). Figure 1 and Figure 2 show the architecture of the TX and RX MMIC. They both integrate a multiplier by three (X3), a buffer amplifier in the LO path and a mixer. Furthermore, the TX integrates a medium power amplifier (MPA) and the RX a low noise amplifier (LNA). For the X3, the buffer amplifier and the LNA stand-alone circuits have been placed, measured and characterized and will be presented here in addition to the measurements of the integrated TX and RX.

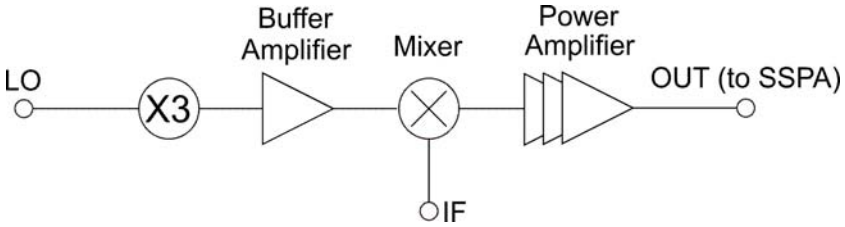

Figure 1: Block diagram of the 300 GHz integrated TX.

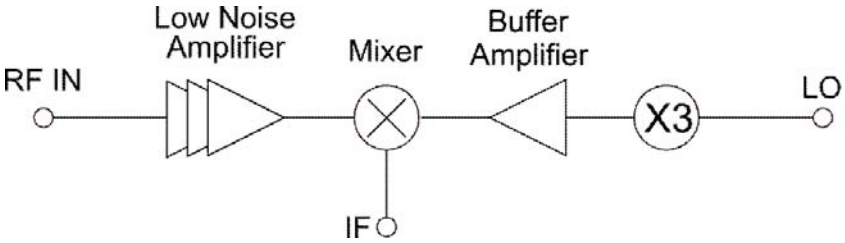

Figure 2: Block diagram of the 300 GHz integrated RX.

6.1. Frequency Tripler

The frequency multiplier has a multiplication factor of three and is based on a transistor biased in class-A mode, which leads to a spectrum rich in odd-order harmonics. The architecture, the schematic and the chip photograph of the X3 have been presented in detail in D4.2. The X3 is measured as described in Section 5.

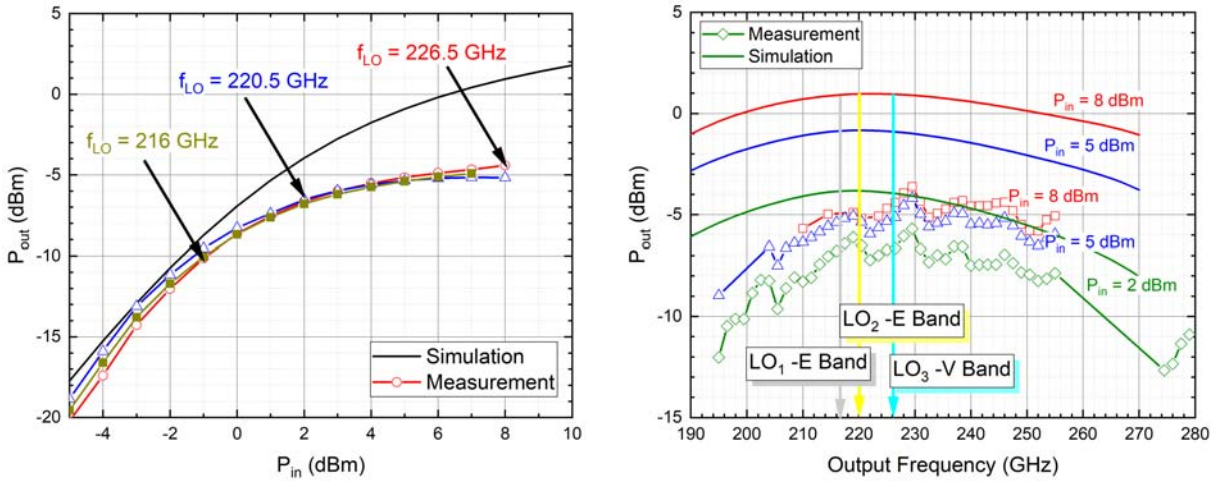

Figure 3: : Measurement results and comparison to simulation for the stand-alone multiplier by three.

Figure 3 shows the measurement results of the X3 compared to the simulation results, which have been presented in D4.2. On the left, the output power is plotted versus the input power. This measurement

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was conducted for different input frequencies, which lead to different output frequencies. The LO frequencies of interest for the ThoR system are: 216.625, 221.625 and 226.11 GHz, where the first two will be used in combination with the E-band IF system and the last one with the V-Band IF system. The measurement shows that the output power curve is constant for different input frequencies and that an input power between 0 and 2 dBm is needed for the tripler to reach a saturated output power. Compared to simulations, there is a good accordance with small differences for low input powers. The difference increases constantly with increasing power, reaching around 5 dB at 6 dBm input power.

On the right, the output power is plotted versus output frequency for different input powers: 2, 5 and 8 dBm. For the LO_1 frequency of interest which will be used in the E-Band system, a difference between simulation and measurement of 3 dB occurs for the 2 dBm input power. This value is similar for the second and third LO frequency of interest. The difference between measurement and simulation grows with increasing input powers, as expected from the measurement on the left. Starting from 4 dBm input power the x3 saturates, while in simulation the saturation is not already reached until 10 dBm.

6.2. Buffer Amplifier

The buffer amplifier is needed to provide enough LO input power for the up- and down-converter. It consists of five gain stages, as presented in D4.2. Small signal S-Parameter measurements were conducted as well as large signal measurements with the help of a power meter.

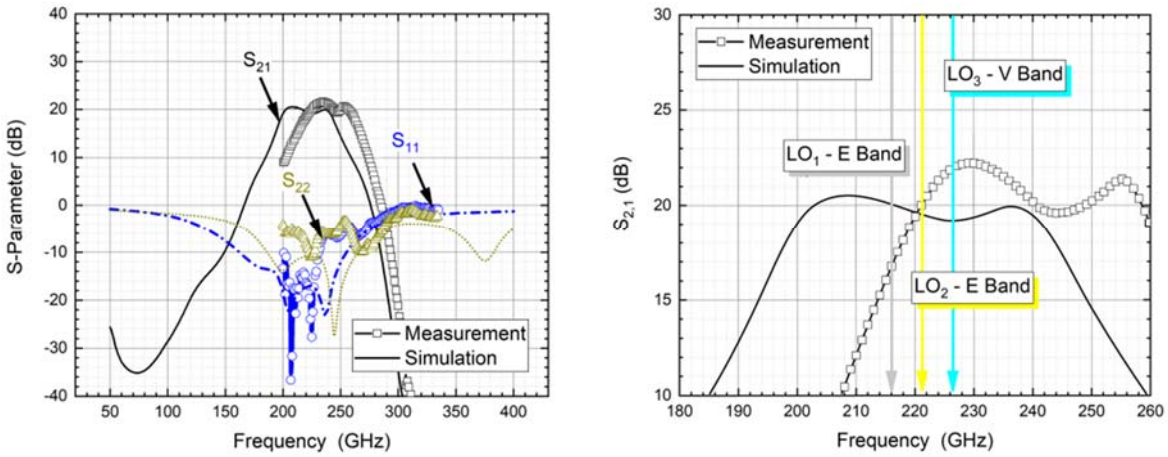

Figure 4: S-Parameter measurement results and comparison to simulation for the buffer amplifier.

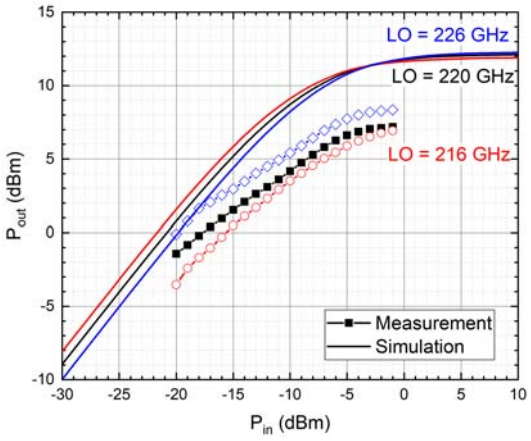

Figure 5: Power measurement results and comparison to simulation for the buffer amplifier.

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Figure 4 shows the measured S-Parameters compared to the simulated one. In the graph on the left, the small signal gain as well as input and output matching over a large frequency range, from 50 to 400 GHz are plotted. On the right only the S21 parameter is plotted over a smaller frequency range, which is of interest in the ThoR system. Here the three LO frequencies are also marked graphically. The frequency of operation of the buffer has moved to slightly higher frequencies and shows a slightly higher gain than simulated. At around 216 GHz, which is the first LO frequency of interest, the gain of the buffer amplifier is around 17 dB. For the V-Band LO frequency, the gain is around 22 dB.

Figure 5 shows the large signal measurement of the buffer for different input frequencies. The slightly deviating small-signal gain between the scalar power measurements and the vectorial S-parameter measurement is mainly due to the different probing and measurement environment. Considering the output power provided by the X3 of around -5 dBm, an output power of above 5 dBm can be supplied by the buffer, independent of the LO frequency. At 226 GHz, this power achieves 8 dBm. Although the frequency of operation has slightly shifted to higher frequencies, this is enough to drive the mixer in saturation.

6.3. Low Noise amplifier

To reduce the noise and make the receiver suitable for terahertz communication a low noise amplifier (LNA) was designed. The architecture and the chip photograph are analyzed in D4.2. S-Parameter measurements of this device were conducted. The results can be seen in Figure 6. The LNA has shifted to lower frequencies, having a large operation bandwidth between 230 GHz and 310 GHz, in comparison to the simulated region between 250 and 330 GHz. Nevertheless, the RF frequency range of interest for ThoR lies in the 3 dB bandwidth of operation of the measured LNA. The input matching network is deteriorated in comparison with the simulation and approaches 0 dB in the frequency band of interest. The output matching is better than -6 dB for RF frequencies between 240 and 310 GHz.

No power measurements were performed yet for the LNA.

Noise measurements are not possible on an on-chip level. This measurement will be performed at the module level.

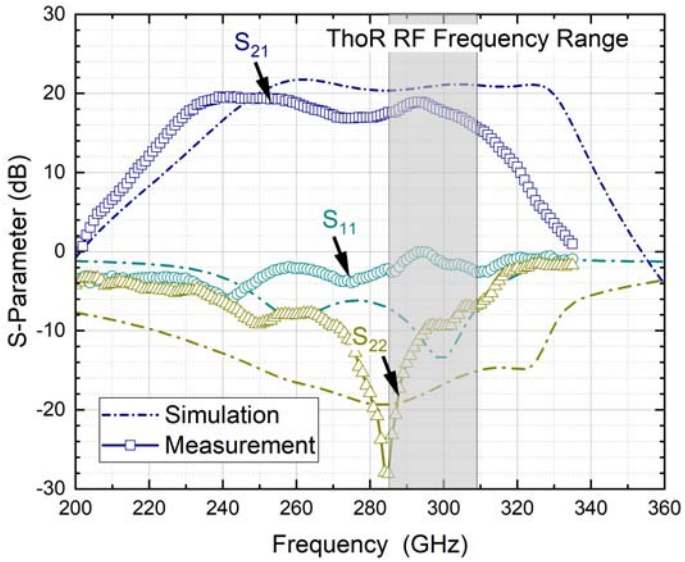

Figure 6: S-Parameter measurement results and comparison to simulation for the LNA.

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6.4. Solid state power amplifier

The 300-GHz high-power amplifier MMIC, which will be packaged in a stand-alone SPPA module, consist of a compact unit amplifier (UA) cell, which is parallelized using Wilkinson power combiners, as described in D4.2 and depicted in the block diagram in Figure 7. In the following subsections (6.4.1 and 6.4.2), the on-wafer measurement results of UA as well PA test circuits are described and evaluated. In subsection 6.4.3, the measured performance of the PA MMICs including waveguide transistions, is shown.

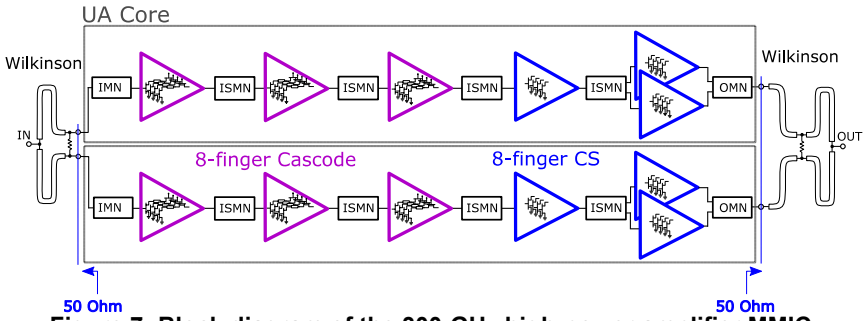

Figure 7: Block diagram of the 300-GHz high-power amplifier MMIC.

Figure 8 shows the chip photograph of the fabricated 5-stage unit amplifier MMIC. The on-wafer measured small- as well as large-signal performance of this break-out circuit is depicted in Figure 9.

The unit amplifier was designed for the 280-350-GHz frequency range, showing a measured small-signal gain ripple of around 5 dB. This gain ripple is mainly caused by the poor isolation of the on-wafer measurement setup. Since the UA's measured S_{12} is only around -40 dB, the depicted periodic gain variation at gain levels above 20 dB can be observed. By including a simple model for the RF-probe overcoupling, a similar behaviour is observed for the simulated S-parameters in Figure 9.

The measured transducer gain and output power versus frequency for CW operation of the UA is shown in Figure 9 on the right. The frequency was swept from 280-328 GHz with 2-GHz step size at -5-dBm available source power. The CS devices in the output stages were biased with 1.3-V drain-source voltage at 400 mA/mm. The drain-supply voltage of the cascode stages is around 2.4 V (V_{DS} = 1.2 V) at 400 mA/mm.

The UA's measured output power is in the range of 8 dBm to 9.7 dBm over the 285-328-GHz frequency range, measured at about 6-dB gain compression. The large-signal gain at this input power level is around 14-15 dB. The UA MMIC includes an 100-µm-long port extension between the RF-pads and the input/output of the UA core, as depicted in Figure 9. This port extension is introducing additional losses of approximately 0.8-1.0 dB at the output, which can be omitted by moving the RF-pad closer to the output of the UA cell.

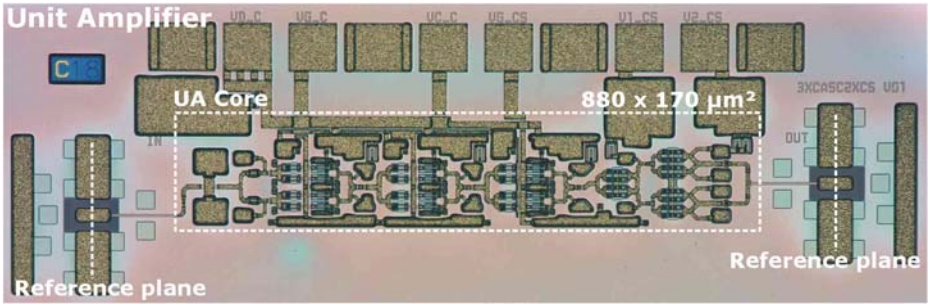

Figure 8: Chip photograph of the five-stage UA MMIC.

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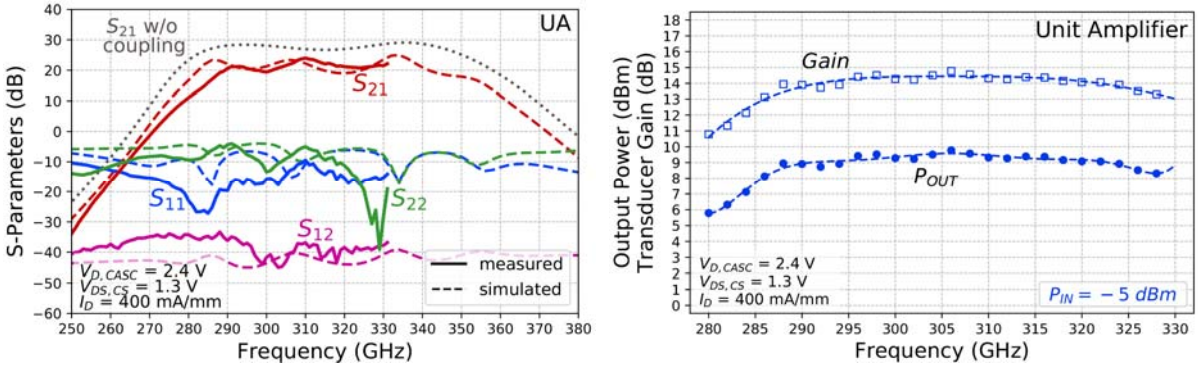

Figure 9: Measured and simulated S-parameters (left) and CW measured transducer gain and output power versus frequency at 5-dBm input power (right) of the unit amplifier MMIC depicted in Figure 8.

6.4.1. 300-GHz High-Power Amplifier Validation

Two high-power amplifier MMICs, PA1 and PA2, have been fabricated for on-wafer characterization, using two different Wilkinson power combiners in the output stage. The chip photographs of PA1 and PA2, which integrate two of the UA cells in parallel, are shown in Figure 10 and Figure 11, respectively.

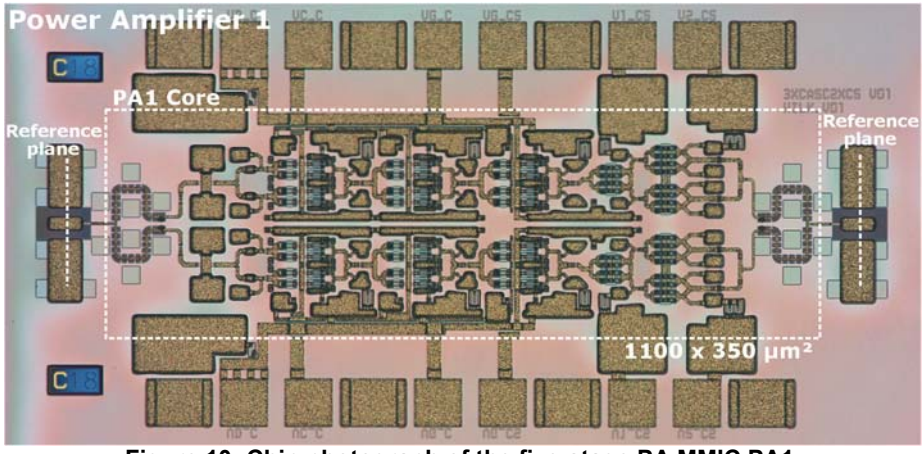

Figure 10: Chip photograph of the five-stage PA MMIC PA1.

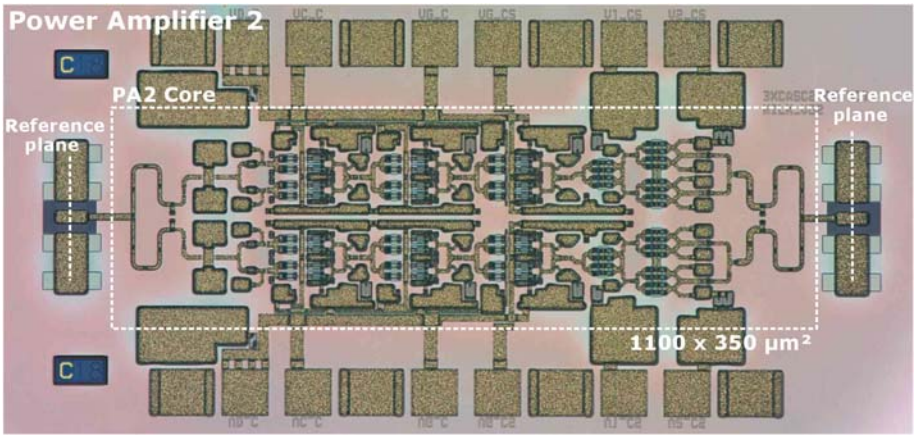

Figure 11: Chip photograph of the five-stage PA MMIC PA2.

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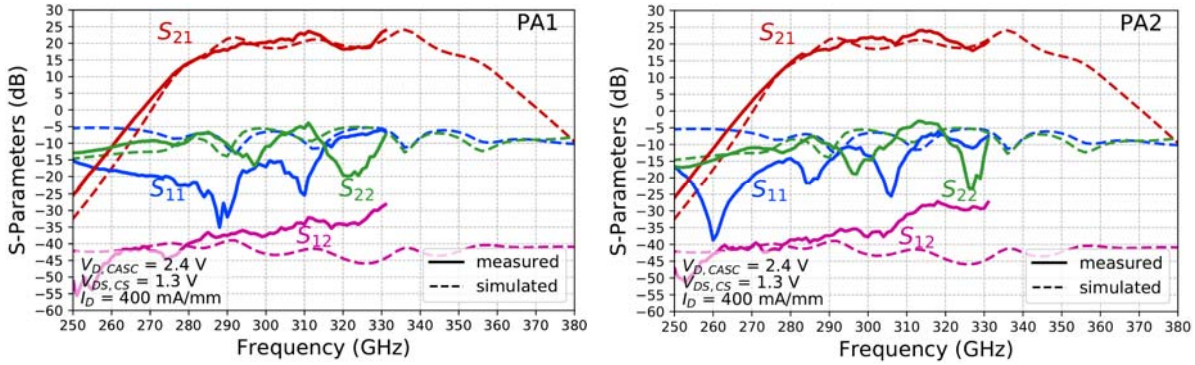

Figure 12: Measured and simulated S-Parameters of the PA MMICs PA1 and PA2.

The measured S-parameters of the two PA MMICs are depicted in Figure 12, showing a good agreement between simulation and measurement with a measured small-signal gain around 20 dB for the frequency range above 290 GHz.

The measured transducer gain and output power of PA1 and PA2 are shown in Figure 13, measured at a constant input power versus frequency. Depicted are the results at -5-dBm as well as at -2-dBm input power. The CS devices in the output stages were biased with 1.3-V drain-source voltage and the cascode cells with 2.4 V (V_{DS} = 1.2 V).

The measured maximum output power level of PA1 is 12.9 dBm, measured at 300 GHz. PA2 achieves up to 13.7 dBm measured output power around 300 GHz, and at least 13 dBm (20 mW) over the 286-310-GHz frequency range. The output power level is increased by more than 3 dB compared to the measurement results of the UA cell, despite the additional loss of the Wilkinson power combiners, which is in the range of 0.6 to 0.8 dB (see D4.2). This is mainly due to the above-mentioned port-extension losses, which are not deembedded from the UA's measurement results. Additionally, since the Wilkinson combiners do not show a perfect 50-Ohm load to the parallelized UA cells, the load at device level in the output stage will differ on a small scale between the UA, PA1 and PA2. Judging from the observed large-signal gain and output-power roll-off above 310 GHz of the PA MMICs compared to the unit amplifier cell, the Wilkinson power combiners need to be slightly optimized in order to further increase the large-signal bandwidth. However, the depicted measurement results perfectly cover the required 285-310-GHz ThoR frequency range with 12-dBm to 13-dBm output power.

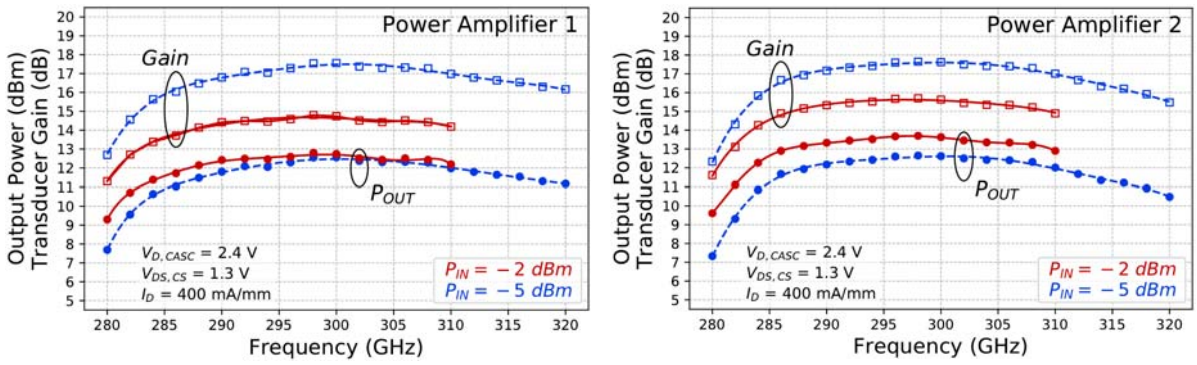

Figure 13: CW measured transducer gain and output power versus frequency of the PA1 and PA2 depicted in Figure 10 and Figure 11, respectively.

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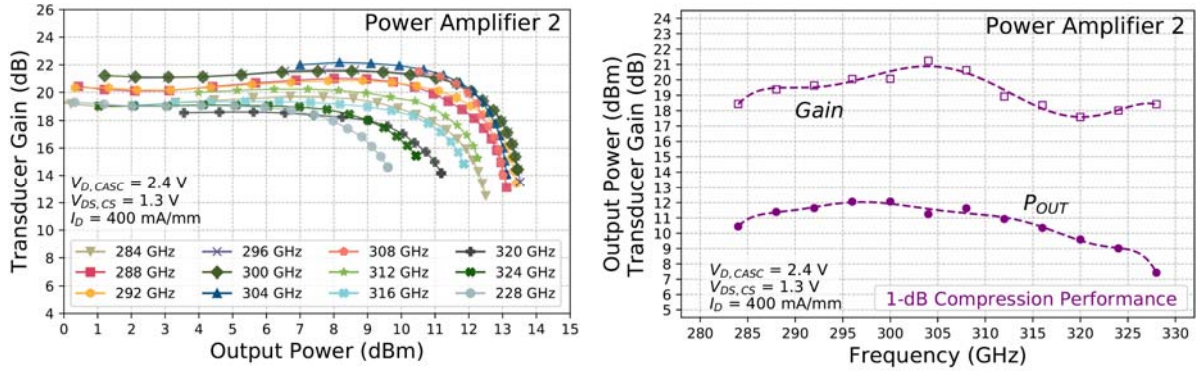

Figure 14: Measured transducer gain vs. measured output power (left) and measured 1-dB compression performance (right) of the PA MMIC PA2 depicted in Figure 12.

Figure 14 (left) shows the measured transducer gain versus measured output power for CW operation of the 300-GHz PA MMIC PA2. The frequency was swept from 284-328-GHz with 2-GHz step size. Alongside high output-power levels above 20 mW, the power amplifier also shows a good linearity and compression behaviour. The measured OP_{1dB} 1-dB gain compression power is above 10 dBm over the 284-316-GHz frequency band, achieving a maximum OP_{1dB} of 12 dBm at 20-dB gain around 300 GHz, as shown in Figure 14 (right).

6.4.2. 300-GHz High-Power Amplifier including Waveguide Transitions

The power amplifier MMICs described above have been designed and fabricated for on-waver characterization and validation of the circuit models only. Based on the designs and results of those compact PA test circuits, the 300-GHz PA MMIC depicted in Figure 15 was designed and fabricated. In contrast to the PA circuits depicted in Figure 10 and Figure 11, additional MMIC to waveguide transitions are integrated.

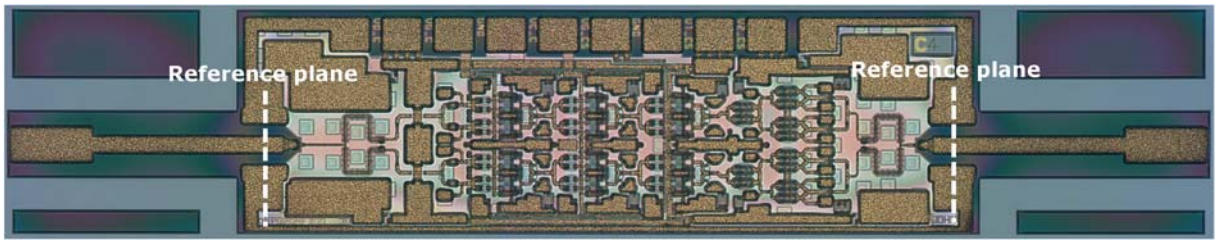

Figure 15: Chip photograph of a 300-GHz high-power amplifier including MMIC-to-waveguide transitions.

The measured S-parameters of the PA MMIC depicted in Figure 15 are shown in Figure 16. The measurements have been conducted on a different run and, hence, different wafer than the measurement results discussed above. The difference in the gain shape between the results shown in Figure 12 and Figure 16 are, however, mainly due to the integrated waveguide-to-MMIC transitions. Since the reference plane of the on-wafer measurements is at the input/output RF-pads of the PA, as depicted in Figure 15, the measurement is affected by the parallel E-field probe. At the lower end of the frequency band of interest, around 265 GHz, the parallel open-circuits stub is presenting a short-circuit to the RF-pads, resulting in the depicted total reflection at the input/output (S11 = 0 dB, S22 = 0 dB). Within the waveguide package, the E-field probe will present a perfect 50-Ohm load to the PA MMIC. By including the MMIC-to-waveguide transitions in the simulation, a good agreement between small-signal simulation and on-wafer measurement is achieved, as can be seen in Figure 16.

Figure 17 shows the CW measured large-signal performance of the PA MMIC. The measured output power at -5 dBm input power is in the range of 8 dBm to 10.8 dBm over the 290-320-GHz frequency

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band. The maximum output power of 10.8 dBm is measured around 305 GHz. In order to evaluate the compression behaviour of the 300-GHz PA MMIC, power-sweep measurements have been conducted. Figure 17 (right) depicts the measured transducer gain vs. measured output power at 300 GHz, showing a gain peaking at small output power levels, which is limiting the measured OP_{1dB} linear output power to 7.5 dBm.

In general, the functionality of the PA MMIC was verified by on-wafer measurements, showing a good agreement between measurement and simulation as well as output power levels above 10 dBm. However, since the parallel E-field probe is affecting the small-signal as well as large signal measurements over the full frequency band of interest (especially at the lower frequencies below 300 GHz), e.g by altering the load impedances at device level at a small scale, the PA depicted in Figure 15 needs to be packaged and characterized at waveguide level, in order to observe the real performance of the MMIC.

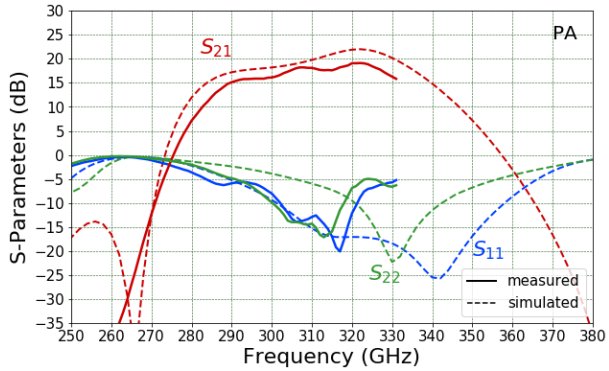

Figure 16: Measured and simulated S-parameters of the 5-stage PA MMIC depicted in Figure 15.

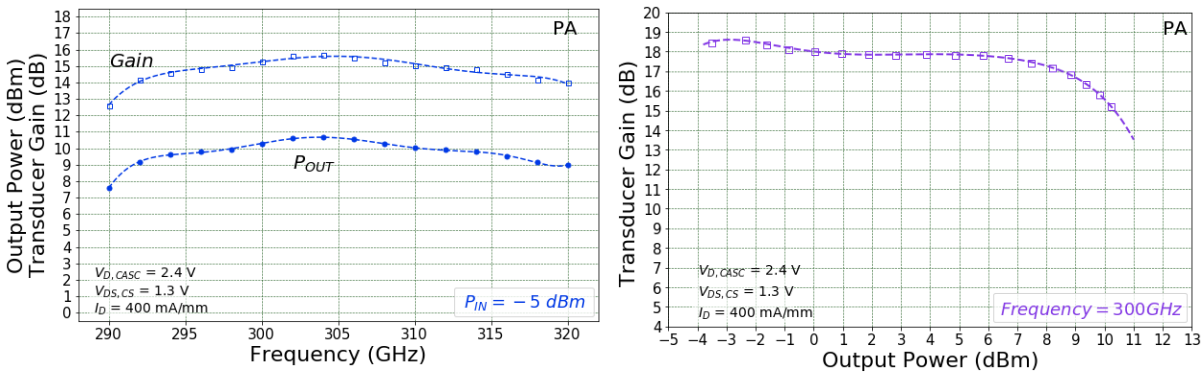

Figure 17: CW measured large-signal performance of the PA MMIC depicted in Figure 15: (left) measured output power and transducer gain vs. frequency at -5 dBm input power and (right) measured transducer gain vs. measured output power at 300 GHz.

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7. Transmitter Measurement

Figure 18 shows the chip photograph of the integrated TX, with a chip size of 0.75 x 3.5 mm. The individual stages integrated in the TX MMIC are graphically marked in the photograph.

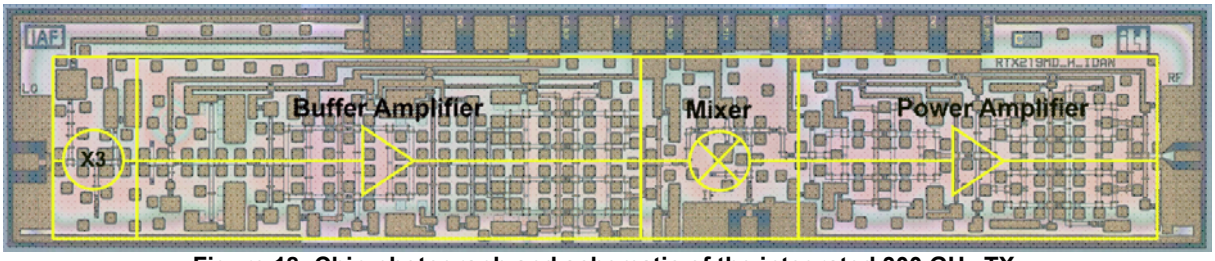

Figure 18: Chip photograph and schematic of the integrated 300 GHz TX.

The first conducted measurement was the LO power sweep, where an optimal LO input power can be determined. Figure 19 shows the results of this measurement and the comparison to simulation, for an LO frequency of 73.5 GHz, an IF frequency of 60 GHz and an IF power of -10 dBm, which assures a linear operation with respect to the IF. For low input powers a good accordance between measurement and simulation can be observed. In saturation region, 2 dB difference between measurement and simulation can be observed. It can also be observed, that in reality the TX saturates earlier than in simulation. Only -5 dBm are enough to saturate the transmitter.

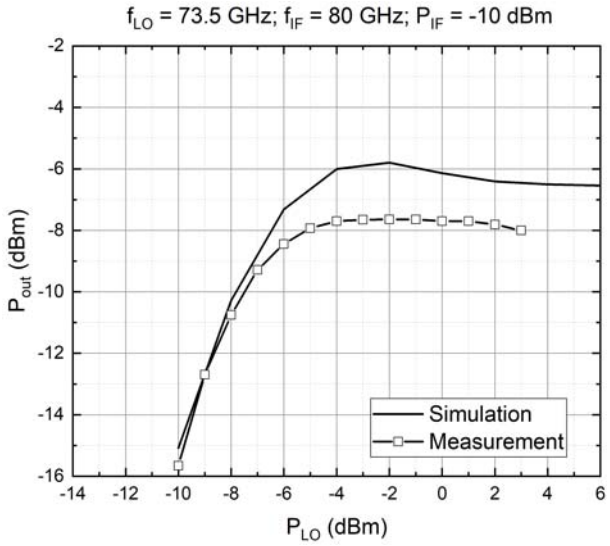

Figure 19: Measurement results and comparison to simulation of the LO power sweep versus output power for the designed TX.

The second conducted measurement was the sweep of the LO frequency. For this measurement different IF frequencies were also swept. Due to measurement restraints no IF frequencies lower than 70 GHz were measured. The LO and the IF powers were kept constant at -2 dBm and -10 dBm respectively. Figure 20 shows the results of this measurement and the comparison to simulation. A good accordance between measurement and simulation, with a deviation below 2 dB, occurs for LO frequencies above 73 GHz. Around the first LO frequency of interest, 72.208 GHz and for IF frequencies below 80 GHz, the difference between measurement and simulation can go up to 6 dB.

Another important conducted measurement is the sweep of the input IF power, which shows the linearity of the transmitter. Figure 21 shows the results of this measurement and the comparison to simulation for an LO frequency of 73.5 GHz, an LO input power of -2 dBm and an IF frequency of 75 GHz. There is a difference of 5 dB output related between measurement and simulation. The $P_{1dB,out}$ is measured to be at -3 dBm. If we consider a 10 dB back-off from this value, which would allow for a complex modulation format like 32QAM, a wireless transmission over a distance of around 80 meters would be

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possible with this transmitter, if an antenna system with a total gain of around 90 dBi would be used in the transmission. For this calculation only this TX is considered. To increase the distance, the SSPA and a TWTA are necessary.

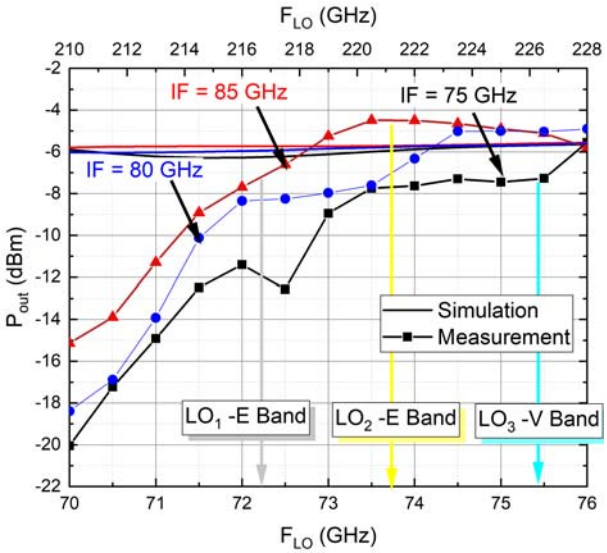

Figure 20: Measurement results and comparison to simulation of the LO frequency sweep versus output power for the designed TX.

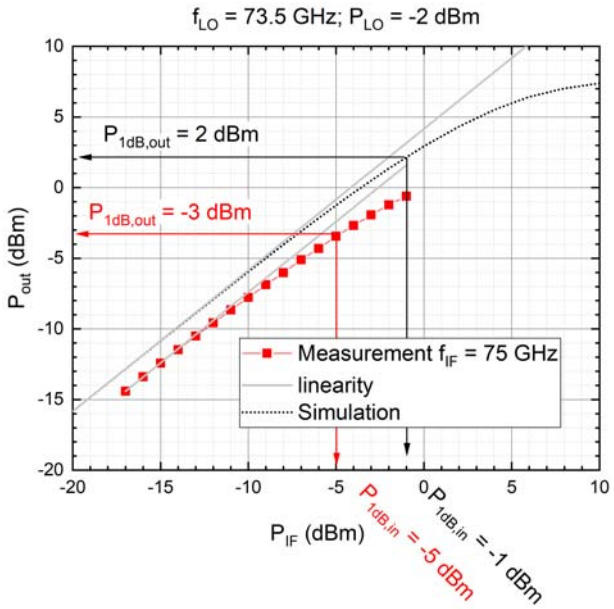

Figure 21: Measurement results and comparison to simulation of the IF input power sweep versus output power for the designed TX.

The final measurement is the measurement of the output power versus IF frequency. Figure 22 shows the results of this measurement for different IF input powers. Like in the previous measurements, the IF frequency is limited to 75 GHz, which is the lower cut-off of WR-10. The LO frequency is 73.5 GHz and the LO input power is -2 dBm. The variation over the IF input power can be observed in the different curves. Very good accordance between measurement and simulation can be observed for lower input powers, as can be seen in the measurement plotted in Figure 22. For -5-dBm input power, the conversion gain is reduced by approximately 1 dB over the full frequency range. This $P_{1dB,in}$ corresponds to the compression behaviour depicted in Fig. 21. The required IF input power level at 10-dB back-off is, therefore, around -15 dBm.

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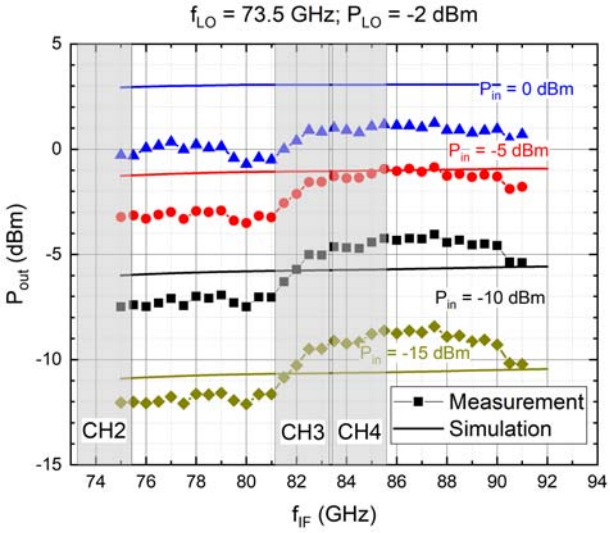

Figure 22: Measurement results and comparison to simulation of the IF frequency sweep versus output power for the designed TX.

8. Receiver Measurement

Figure 23 shows the chip photograph and the schematic of the designed RX MMIC, which includes an X3, a buffer amplifier, a down-converter and an LNA. The chip dimensions are identical to the one of the transmitter: 0.75 x 3.5 mm.

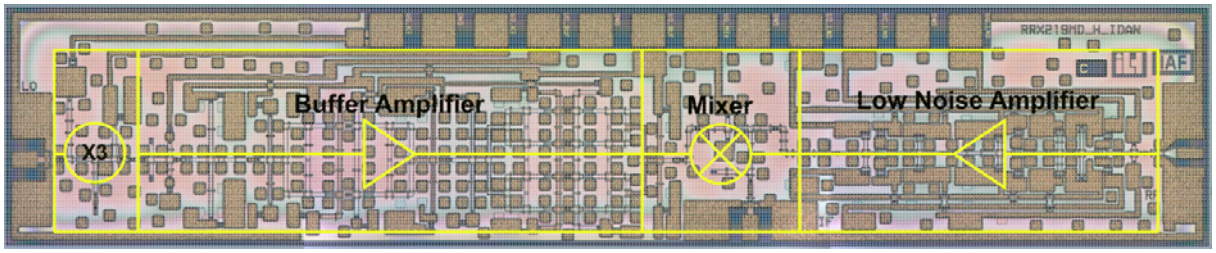

Figure 23: Chip photograph and schematic of the integrated RX.

Three measurements of the conversion gain were conducted for the integrated RX: under the variation of the LO power, of the RF frequency and RF power. The results of these measurements can be seen in Figure 24, Figure 25an Figure 26. The measurement presented in Figure 24 is conducted at an LO frequency of 73.5 GHz, an RF frequency of 300.5 GHz and an RF input power of -34 dBm, which assures linear operation. The receiver starts to saturate at around -2 dBm input power and has a saturated conversion gain of around 8 dB for this combination of LO and RF frequency. A constant 4 dB difference between measurement and simulation can be observed for the whole power range.

The bandwidth of the RX is dependent on the used LO frequency, as can be seen in Figure 25, in the left graph. For an LO of 72 GHz, which will be used in combination with the E-Band modems, an approximate RF frequency of interest between 288 and 303 GHz is reached. This corresponds with the 3 dB bandwidth of the RX for this LO frequency. For an LO of around 73.5 GHz, which will also be used with the IF system in the E-Band, an RF frequency between 293 and 308 GHz is of interest. In this range, the maximum conversion gain is around 11 dB and the minimum at around 8 dB, which means the 3 dB RF bandwidth corresponds to the RF frequency of interest for this LO. The last LO frequency of around 75.5 GHz will be used with the V-Band modems, which leads to an RF frequency between 285 and 290 GHz. The possible measurement range for this LO frequency starts at only 291.5 GHz, limited by the measurement setup of the IF port. Therefore, no information about this RF frequency band

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can be made. Compared to simulations, there is a good agreement, with deviations below 2 dB, for the LO frequencies of 220.5 and 226.5 GHz in the RF frequency range between 303 and 313 GHz. Below this RF frequency band and for the LO frequency of 216 GHz the deviation is higher, peaking at 8 dB for 285 GHz. For an optimal input power, of around -40 dBm, this results into an IF output power between -36 dBm and -29 dBm. This falls into the power range required by both modem systems, making a difference between measurement and simulation not problematic. The right graph in Figure 25 shows the same measurement as the on plotted on the left with the only difference, that the variation of the IF frequency is represented instead of the RF frequency. The desired channels for the E-Band are also marked with coloured rectangles. This shows that in the frame of each channel with a bandwidth of 2 GHz the conversion gain and therefore, the received input power, is more or less constant, with differences below 1 dB.

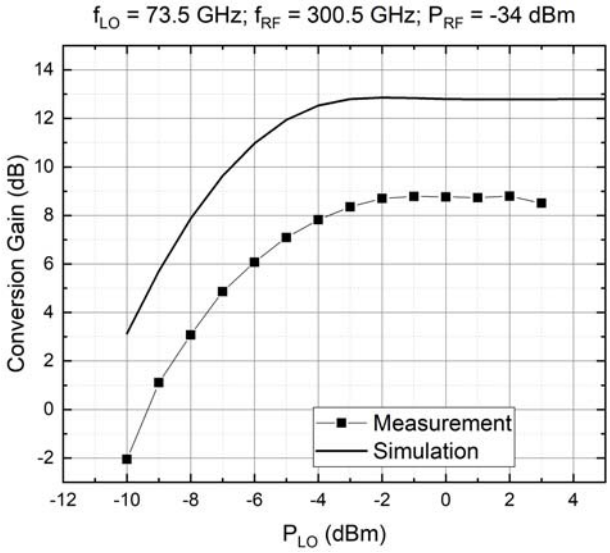

Figure 24: : Measurement results and comparison to simulation of the LO power sweep versus conversion gain for the designed RX.

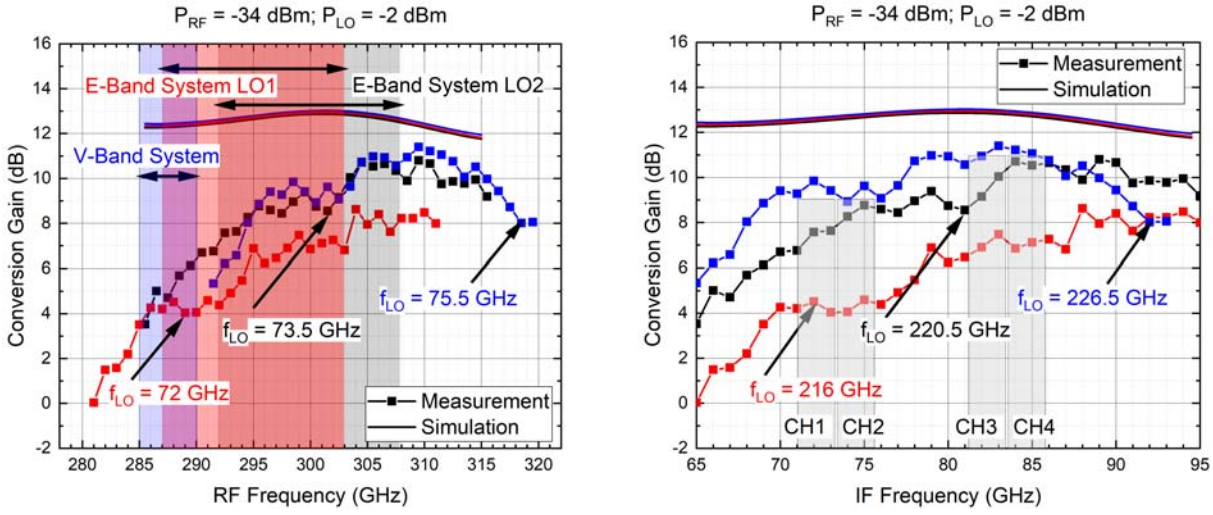

Figure 25: Measurement results and comparison to simulation of the RF and IF frequency sweep versus conversion gain for the designed RX.

The linearity of the RX can be seen in Figure 26. The measurement was conducted with a constant LO frequency of 75.5 GHz, at an input power of -2 dBm and three different RF frequencies: 301.5, 306.5 and 312.5 GHz. A deviation of around 4 dB can be observed between measurement and simulation. A

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maximum conversion gain of around 13 dB was simulated, while measured the conversion gain only reached a maximum of around 9 dB for an RF of 301.5 GHz and 11 dB for the other two RF frequencies. The measured 1 dB compression point is 3 dB lower than the simulated one, at -26 dBm RF input power. To be able to transmit complex modulation formats, like 32 and 64QAM more than 10 dB back off from the 1 dB compression point is necessary. This means that the -40 dBm optimal input power was a good assumption, assuring a good linearity of the receiver. Depending on modulation format this optimal input power might vary to higher values.

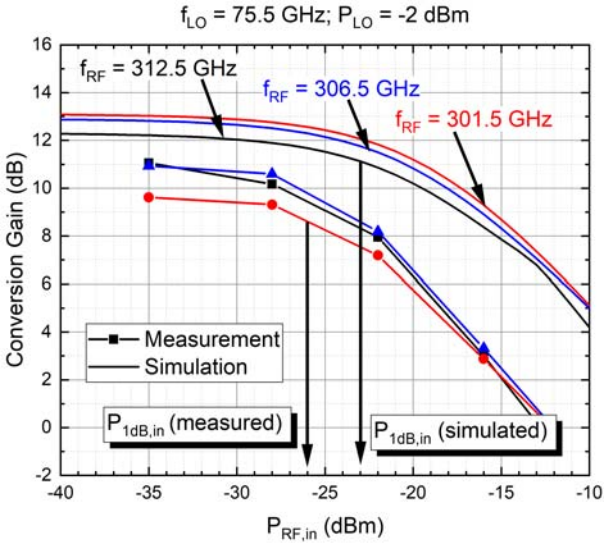

Figure 26: Measurement results and comparison to simulation of the RF power sweep versus conversion gain for the designed RX.

Furthermore, a second receiver with an active down-converter was placed and fabricated. An active mixer has the advantage of using a lower LO input power, thus the buffer amplifier in the LO path becomes obsolete. This leads to the immediate advantage of chip space reduction. On the down-side active mixers have a lower linearity than the passive ones. Figure 27 shows the chip photograph of the active receiver.

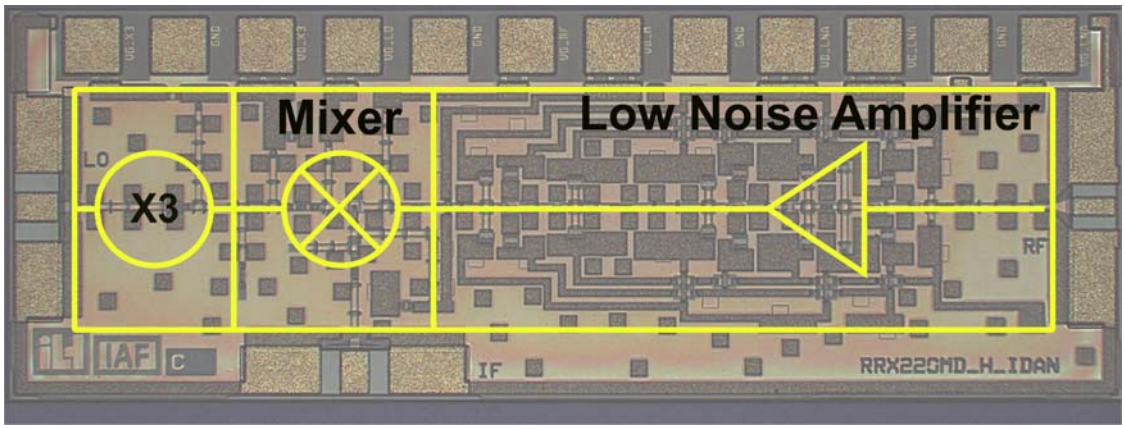

Figure 27: Chip photograph of the receiver using an active mixer. The chip size is 0.75 x 2 mm².

The characterization of this MMIC chip is done using three measurements, like for the previous passive down converter. The conversion gain is measured under the variation of the LO input power, RF frequency and RF input power.
Figure 28 shows the measured conversion gain versus LO input power. The RF input power is kept constant at -44 dBm and three combinations of LO and RF frequencies are swept. The RX starts to

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saturate at around 2 dBm and has a maximum conversion gain between 12 and 15 dB. The black and the blue curve represent two cases where the E-Band IF system will be used.

The conversion gain dependency on the RF frequency can be seen in Figure 29. The RF input power is set to -44 dBm and the LO input power to 3 dBm. For an LO of 72 GHz the conversion gain spans between 8 and 14 dB, hence the ThoR RF frequency, marked in **Fehler! Verweisquelle konnte nicht gefunden werden.** represents the 6 dB bandwidth of the active receiver for this LO frequency. This statement is also true for an LO of 73.5 GHz. For an LO of 75.5 GHz which will be used in combination with the V-Band system the RF band spans from 285 to 290 GHz. In this region the conversion gain averages around 12 dB with small deviations, below 1 dB.

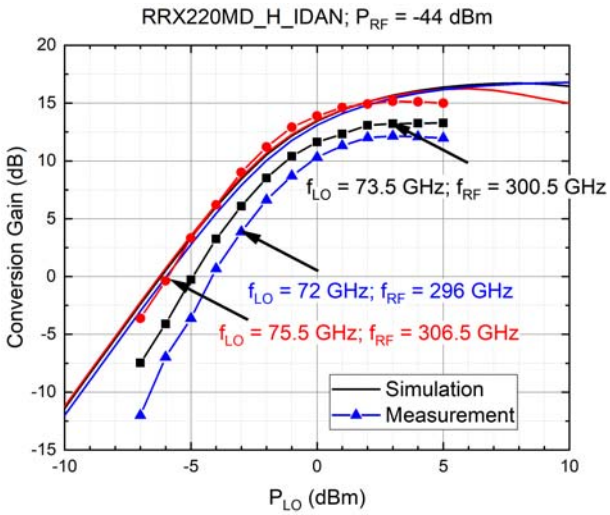

Figure 28: : Measurement results and comparison to simulation under the variation of LO input power for the active RX.

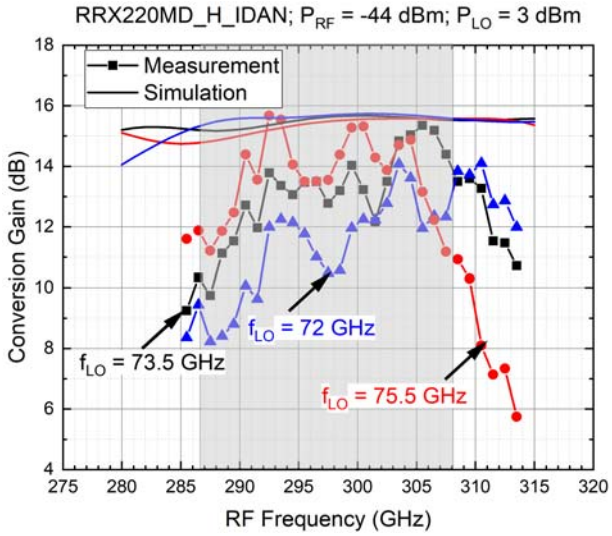

Figure 29: Measurement results and comparison to simulation under the variation of RF frequency for the active RX.

A well-known disadvantage of the active mixers is the poor linearity in comparison to the passive ones. This has been measured for the designed receiver and the results can be seen in Figure 30. The measurement is conducted for a fix LO frequency of 73.5 GHz at an input power of 3 dBm and for different IF frequencies. The 1 dB compression point input related lies at around -38 dBm. Depending on the transmitted RF frequency this translates to an output power of around -26 dBm. A 10 dB back off

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from this point ,which would allow for the transmission of complex modulation formats, leads to powers around -36 dBm at the RX input of the IF system, which is the minimum requirement for the E-Band modems.

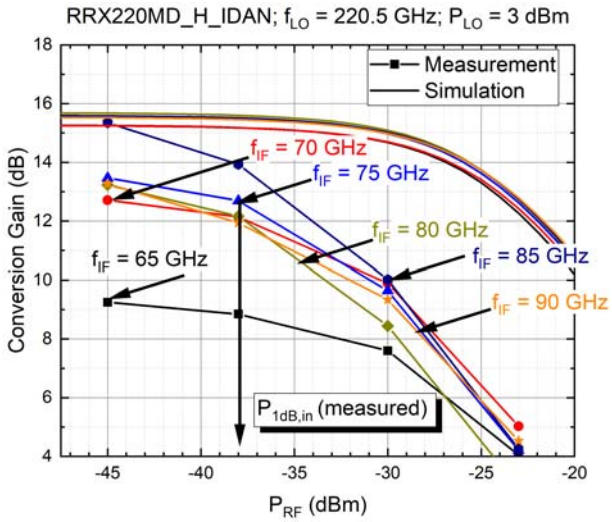

Figure 30: Measurement results and comparison to simulation under the variation of RF input power for the active RX.

For a better understanding of the advantages and disadvantages of the active receiver, a comparison with the passive one has been made and the results are summed up in Table 1. Both receivers cover the desired RF frequency band, from 285 to 309 GHz, the spread for the active RX is 1 dB higher than the one of the passive RX. The passive RX is clearly more linear, while the active RX shows the big advantages of a smaller chip space and a lower DC consumption. Since, the DC consumption is not a concern for this link, the most important question is if the advantage of a smaller chip, which reduces the risk of failure at packaging is worth taking to the detriment of a poor linearity. Since the active RX respects the requirements set by the E-Band modems, but is at the lowest limit, the passive receiver is chosen to be used in the ThoR system.

Table 1: Comparison between the measured passive and active RX.

	Passive RX	**Active RX**
RF Frequency 285 – 309 GHz	7 dB BW	8 dB BW
1 dB compression point (input related)	-26 dBm	-38 dBm
IF output power (at 10 dB back off)	-26 dBm	-36 dBm
Chip space	2.625 mm^2	1.5 mm^2
DC power consumption	262 mW	85 mW

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9. Summary and Conclusion

This document describes the on-wafer measured performance of the 300-GHz ThoR front-end MMICs, the evaluation of the 300-GHz high-power amplifier MMICs as well as stand-alone test circuits of frequency multiplier and amplifier MMICs. The design of the fabricated and measured circuits was discussed and described in detail in D4.2 [2].

The results of the on-waver characterization are discussed in detail, considering the requirements in the context of the overall system implementation, and summarized in the following:

- The 300-GHz receiver and transmitter MMICs have been characterized on wafer, and the functionality has been verified for the relevant ThoR frequency range, limited to IF frequencies above 65 GHz by the available measurement setup.
- The measured TX MMIC shows a good agreement with the simulation for LO frequencies above 72 GHz, with a linear output power (P_{1dB}) of -3 dBm.
- Two 300-GHz RX MMICs have been fabricated and characterized. For packaging and system integration, the RX implementation including the resistive down converter is chosen, due to its better linearity. The conversion gain of this MMIC is in the range of 8 to 10 dB, with a linear output power at IF frequencies of -16 dBm, suitable for system implementation with the IF modems.
- The measured test circuits of the 300-GHz high-power amplifier MMICs demonstrate state-of-the-art output power levels above 20 mW, with a linear output power above 10 dBm over the 284-316-GHz frequency band. The MMIC including waveguide transitions is functional, and needs to be characterized in the package.

Based on the verified performance of the front-end and amplifier MMICs, the waveguide modules for MMIC packaging are planned and fabricated, in order to advance the 300-GHz solid-state system components in WP4.

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10. References

[1] I. Dan, L. John and I. Kallfass, “D2.3 Specifications of RF Design,” Jan 2019.

[2] I. Dahn, I. Kallfass and L. John, "D4.2 RF Circuit Design", Jan 2020

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