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

ThoR

Deliverable D4.4

Solid-state RF Front-End Test Validation

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RE	**Restricted to a group specified by the consortium (including the Commission Services)**	
CO	**Confidential, only for members of the consortium (including the Commission Services)**	

Contents

Change register

Version	Date	Author	Organisation	Changes
A	29-May-2020	Laurenz John Dominik Wrana, Ingmar Kallfass	IAF USTUTT	First full draft
B	13-Aug-2020	Laurenz John	IAF	CW measurement results added
C	28-Aug-2020	Laurenz John	IAF	1st revision

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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
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2. Abbreviations

IF	Intermediate Frequency
InGaAs	Indium Gallium Arsenide
LNA	Low Noise Amplifier
LO	Local Oscillator
mHEMT	metamorphic High Electron Mobility Transistor
MMIC	Millimetre-wave Monolithic Integrated Circuits
P_{-1dB}	1 dB compression point
PA	Power Amplifier
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RX	Receiver
SSPA	Solid State Power Amplifier
TX	Transmitter
RX	Receiver

3. Executive summary

This deliverable reports on the measurement and characterization results of the packaged 300-GHz front-end and power amplifier modules developed in WP4. The modules are based on the InGaAs mHEMT MMICs reported in D4.3 and will be used in the upcoming live demos in the ThoR project.

The functionality of the 300-GHz power amplifier as well as the receiver and transmitter front-end modules is verified within the requirements for overall system implementation in the ThoR project, permitting the use in the planned live demos in WP6.

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.

This deliverable describes the measurement results of the 300-GHz front-end modules including a 300-GHz high-power amplifier, which have been developed in T4.3 of WP4. The packaged MMICs have been designed based on the specifications described in 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 integrated in the 300-GHz front-end MMICs, was reported in detail in D4.2 RF Circuits Design [2] – and the on-wafer measurement results were described in D4.3 [3]. In the following sections, the measured performance of the PA and up-/down-converter modules are discussed.

The front-end modules have been characterized after assembly using continues wave test signals in laboratory environment. These stand-alone 300-GHz modules and their respective performance is described in detail in Section 5 and Section 6. The measurement setups for the conducted module characterization have been described previously in D4.3 [3].

5. 300-GHz Front-End Modules

The RF system, as described in detail in WP4, D4.2 consists of a 300-GHz transmitter (TX), a solid state power amplifier (SSPA) and a 300-GHz receiver (RX). Figure 1 and Figure 2 show the simplified functional block diagrams of the packaged TX and RX, respectively. The transmit and receive MMICs both integrate a multiplier by three (X3), an LO buffer amplifier and a mixer. In addition to these subcircuits, medium-power and low-noise amplifier cells are integrated in the TX's RF-output stage and the RX's RF-input stage, respectively. The MMICs are pin compatible and are integrated in the M265RXTX module series using Fraunhofer IAF's split-block waveguide packaging technology. This module series was developed for the ThoR front ends and is described detail in the following.

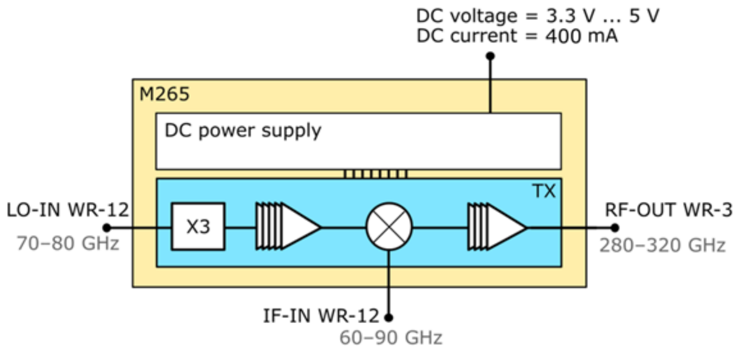


Figure 1: Functional block diagram of the 300-GHz M265 transmitter module.

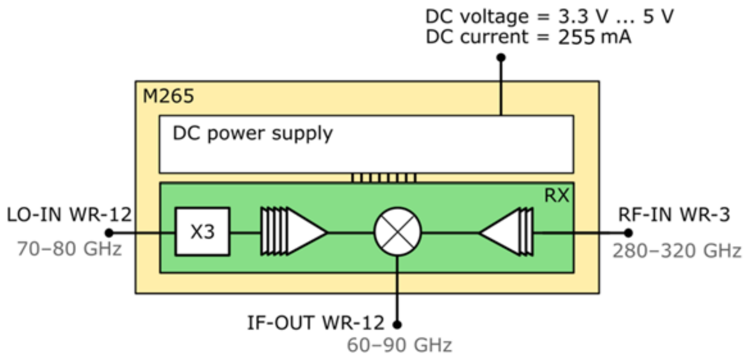
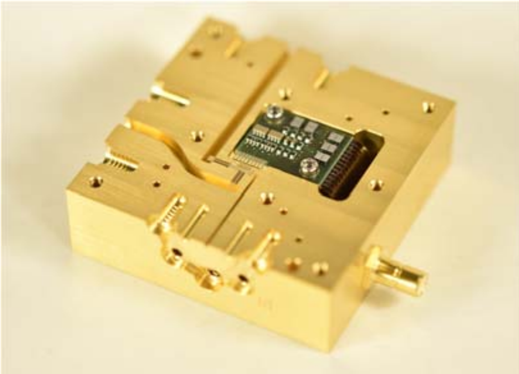


Figure 2: Functional block diagram of the 300-GHz M265 receiver module.

The packaged M265 front ends include a DC power supply for bias control and current sensing. The required external positive supply voltage is in the range of 3.3 V to 5 V. The typical external DC current is around 255 mA for the RX module and 400 mA for the TX module. Hence, the resulting DC power consumption of the front-end modules is in the range of 1 W to 1.5 W for 3.6-V external supply voltage. The interface for LO/IF is the E-band WR-12 waveguide and WR-3 waveguide for the 300-GHz RF band, as described in D2.3 Specification of RF Design [1].

The MMICs are packaged into gold plated brass modules in split-block configuration. Figure 3 shows the lower half of an assembled front-end module including the close-up view of a packaged 300-GHz receiver MMIC on the right. To couple the signals to and from the waveguides, E-plane probes are used which have been processed on a 50-µm quartz substrate. The connection from the quartz microstrip line to the MMIC is then realized via bond-wire connection.

The quartz transitions for the LO and IF transitions were designed to cover the extended E-band from 57 GHz to above 90 GHz with a return loss better than 15 dB and an insertion loss below 1 dB. The insertion loss of the 300-GHz MMIC-to-waveguide transition, on the other hand, is typically in the range of 1 dB to 2 dB, as described in [4].



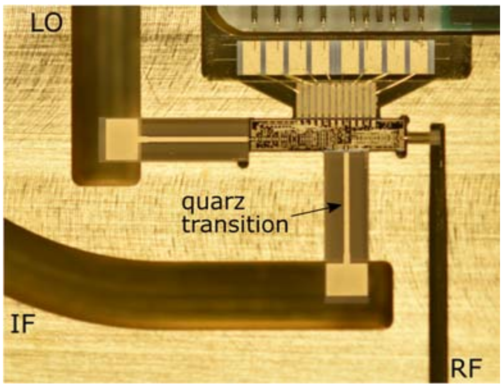


Figure 3: Lower half of the M265 split block module (left) and close-up view of the packaged front-end MMIC including quartz transitions (right).

The front-end modules were initially tested and characterized by RF continuous wave (CW) test signals, which is described in detail in the following sections.

5.1. Receiver Module

Fig. 4 shows the photograph of the M265RRXH receiver module. The module was measured at waveguide level using the measurement setup described in D4.3 [3]. This measurement setup, however, includes a WR-10 waveguide connection for the IF frequencies. This WR-10 setup was used for the RX characterisation, since no WR-12 extension module was available for IF-signal measurements in the targeted frequency range of 58 to 85 GHz. Hence, the IF-frequency range was limited to the lower WR-10 cut-off frequency around 60 GHz.

Figure 4: Photograph of the 300-GHz RX module.

The measured conversion gain vs. LO power and vs. LO frequency of the 300-GHz receiver module for CW operation is shown in Fig. 5. The conversion gain vs. swept LO input power at 80-GHz IF frequency is depicted in Fig. 5 on the left, showing saturated conversion-gain behaviour for LO-input power levels exceeding 0 dBm when the LO frequency is chosen above 72 GHz. For a 70-GHz LO frequency, on the other hand, higher LO-power levels are required. Hence, the receiver measurements over the 70–75.5-GHz LO frequency range have been conducted at a constant LO-power level of 3 dBm.

The increasing conversion gain towards higher LO frequencies – which can be seen in Fig. 5 – is mainly caused by the gain slope of the integrated 220-GHz LO-buffer amplifier and 300-GHz LNA circuits. Especially for IF frequencies above 85 GHz – which is outside of the targeted frequency range in ThoR – a strongly increasing conversion gain is observed. Within the ThoR-relevant 70-GHz and 80-GHz IF frequencies, the conversion gain is in the range of 3 to 5 dBm over the 71–75-GHz LO frequency range.

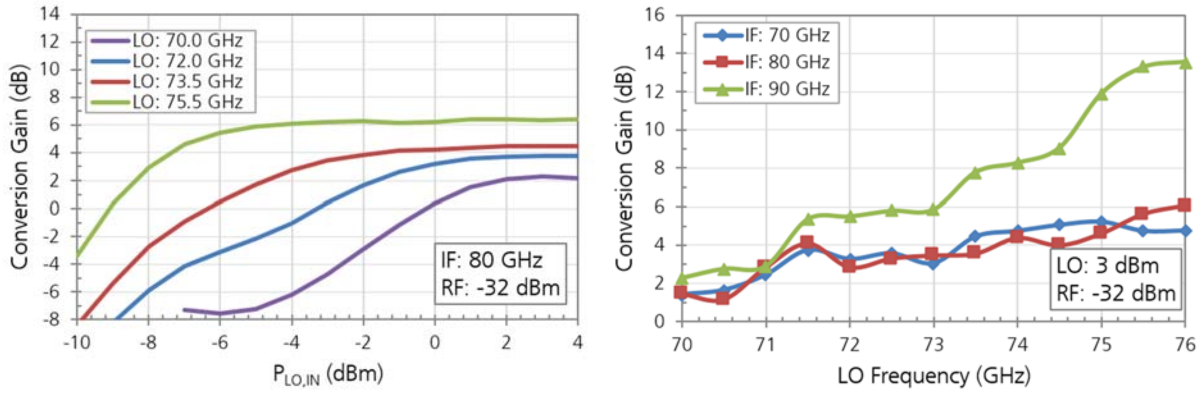


Figure 5: Measured conversion gain vs. LO power and vs. LO frequency of the receiver module for CW operation. Left: conversion gain vs. LO input power at 70–75.5-GHz LO frequency, 80-GHz IF frequency and –32-dBm RF power. Right: conversion gain vs. LO frequency at 70–90-GHz IF frequency, 3-dBm LO power and –32-dBm RF power.

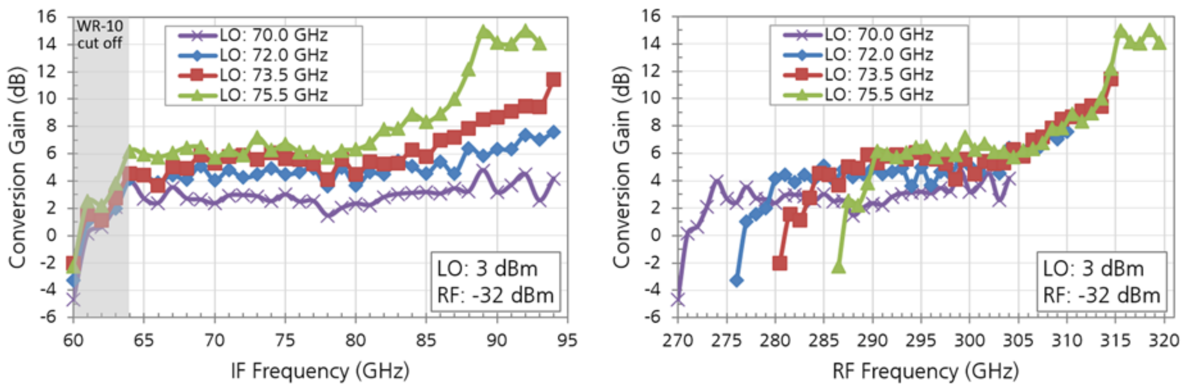


Figure 6: CW measured conversion gain (CG) vs. IF/RF frequency of the receiver module. The CG is depicted for 70–75.5-GHz LO frequencies at 3-dBm LO power and –32-dBm RF power, respectively. Left: plotted vs. the IF frequency from 60 GHz to 94 GHz. Right: plotted vs. the respective RF frequency range of 270–320-GHz.

The CW measured conversion gain vs. IF/RF frequency of the receiver module is depicted in Fig. 6. The conversion gain was measured at 70–75.5-GHz LO frequencies and 3-dBm LO power for IF frequencies in the range of 60 to 95 GHz – plotted vs. the IF frequency range in Fig. 6 on the left and plotted vs. the corresponding RF frequency range on the right. For IF frequencies below 64 GHz a steeply decreasing conversion gain is observed, which is caused by the increasing losses and decreasing return loss of the WR-10 waveguide at the lower cut-off frequency around 60 GHz.

However, over the IF-frequency band of 64–85 GHz, which is the main IF-frequency band of interest in the ThoR project, a broadband behaviour with 4–6-dB conversion gain is observed for LO frequencies above 70 GHz. For 72-GHz LO frequency, the corresponding 3-dB bandwidth is at least 30 GHz. The increasing conversion gain for frequencies above 305 GHz (Fig. 6, right) is caused by the gain slope of the integrated LNA circuit.

The measured conversion gain of the receiver module at different RF-input power levels is depicted in Fig. 7 and Fig. 8. Fig. 7 shows the conversion gain measurement vs. IF/RF frequency at 75.5-GHz LO frequency and RF-power levels of –25 dBm, –18 dBm and –12 dBm. The compression behaviour of the receiver, furthermore, can be seen Fig. 8. The measured IP_{1dB} RF-input power is around –23 dBm, which corresponds to output power levels at IF in the range of –17.5 dBm for 70-GHz IF frequency and –15.5 for 85-GHz IF frequency.

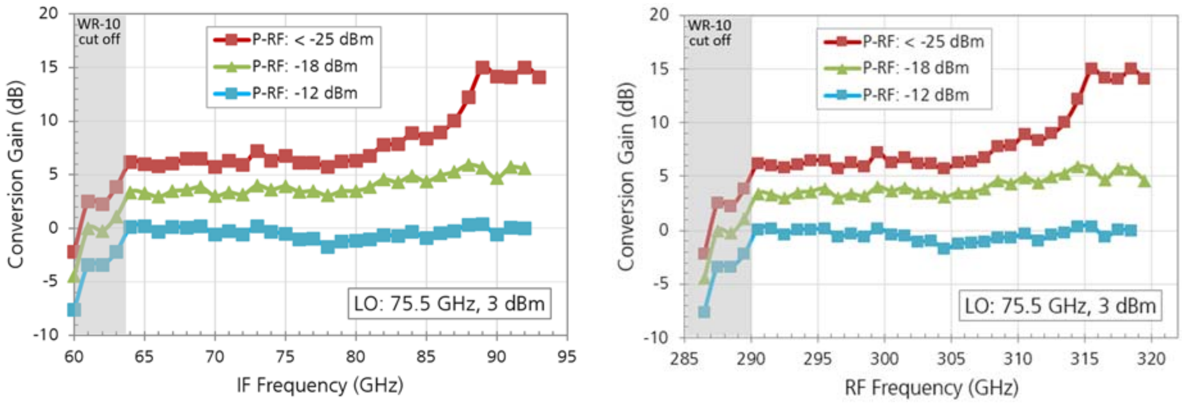


Figure 7: Measured conversion gain for different RF input power levels. The conversion gain is plotted vs. IF frequency (left) and vs. the corresponding RF frequency (right) at 75.5-GHz LO frequency and 3-dBm LO power.

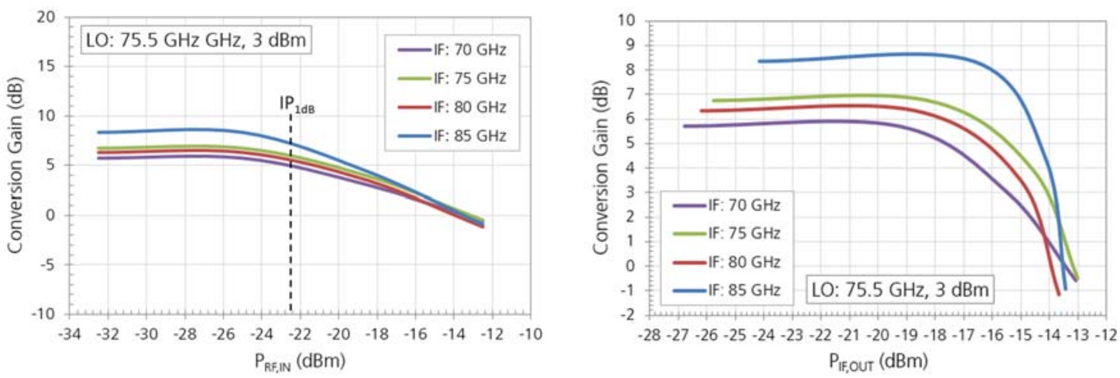


Figure 8: Measured conversion gain for different RF input power levels. The conversion gain is plotted vs. IF-input power (left) and vs. the corresponding RF-output power (right) at 75.5-GHz LO frequency and 3-dBm LO power.

5.2. Transmitter Module

The photograph of an M265RTXH transmitter module is depicted in Fig. 9. The transmitter was characterized using two different IF sources to cover the 60 to 90 GHz IF-frequency range. Up to 75 GHz, a V-band setup was used and above 75 GHz, a W-band source was employed. The whole measurement setup is described in more detail D4.3 [3].

Fig. 10 on the left shows the measured RF-output power vs. swept LO input power for different LO frequencies. Since the same integrated LO chain is used for the TX as for the RX (x3, buffer amplifier), the same LO-power-sweep behaviour is observed for the transmitter as for the receiver in Fig. 5. For LO-input power levels above 2 dBm, no significant increase in conversion gain is observed for the depicted frequencies. By increasing the LO frequency above 72 GHz, however, significantly reduced LO power levels are required to saturate the RF-output power. The corresponding measured RF-output power vs. LO frequency for IF frequencies in the range of 60–90 GHz is shown in Fig. 10 on the right.

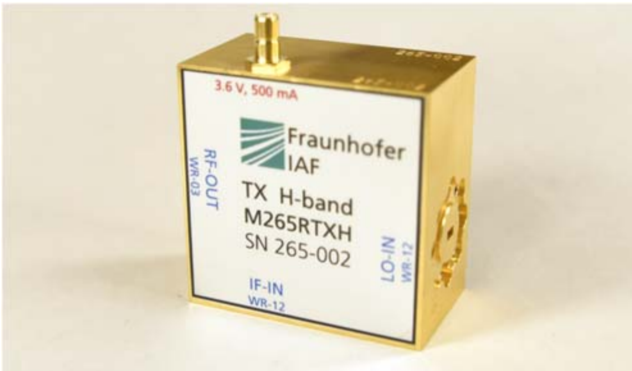


Figure 9: Photograph of the 300-GHz TX module.

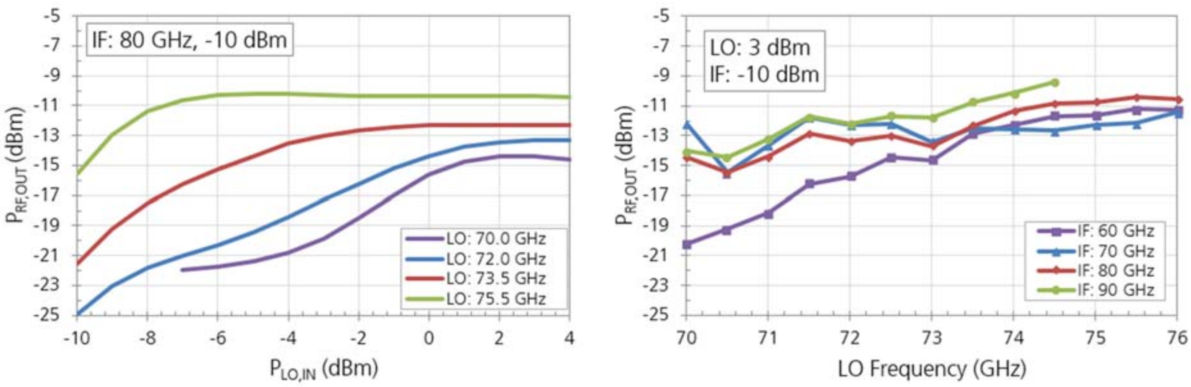


Figure 10: Measured RF-output power vs. LO power and LO frequency of the transmitter module for CW operation. Left: RF-output power vs. LO input power at 70–75.5-GHz LO frequency, 80-GHz IF frequency and –10-dBm IF power. Right: RF-output power vs. LO frequency at 70–90-GHz IF frequency, 3-dBm LO power and –10-dBm IF power.

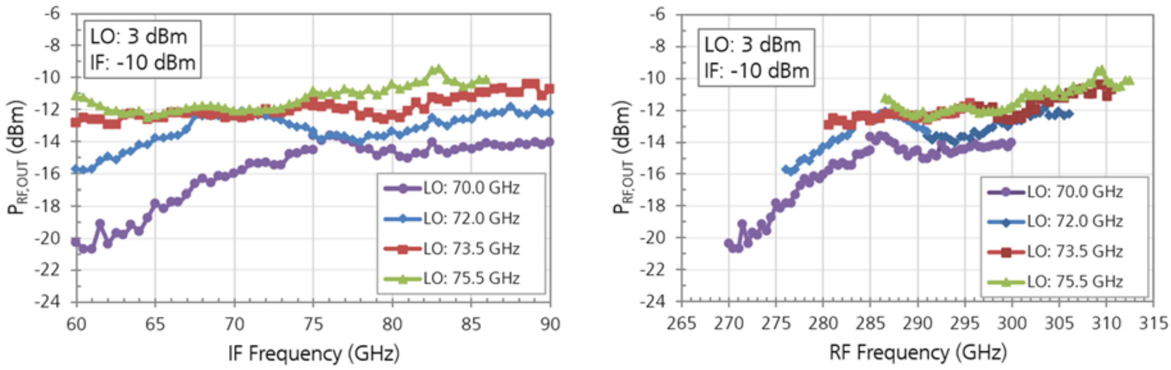


Figure 11: Measured RF-output power vs. IF/RF frequency of the transmitter module for CW operation. The output power is depicted for 70–75.5-GHz LO frequencies at 3-dBm LO power and –10-dBm IF power, respectively. Left: plotted vs. the IF frequency from 60 GHz to 90 GHz. Right: plotted vs. the respective RF frequency range of 270–315-GHz.

The CW measured RF-output power plotted vs. the IF-input frequency and the corresponding RF-output frequency is depicted in Fig. 11. Depicted are the results for LO frequencies in the range of 70 to 75.5 GHz over the IF frequency band of 60–90 GHz. For 73.5 GHz LO frequency, the 3-dB bandwidth is at least 30 GHz with output power levels in the range of –13 to –10 dBm – measured at –10-dBm IF-input power. The decreasing gain at lower IF frequencies for the LO frequencies of 70 GHz and 72 GHz is due to the fact, that the corresponding RF frequencies are below the 285–320-GHz frequency of operation of the integrated 300-GHz medium-power amplifier circuit. This can be seen in Fig. 11 on the right. Over the frequency band of 280 to 310 GHz, RF-output power levels around -12 to -10 dBm were measured for LO frequencies above 73 GHz.

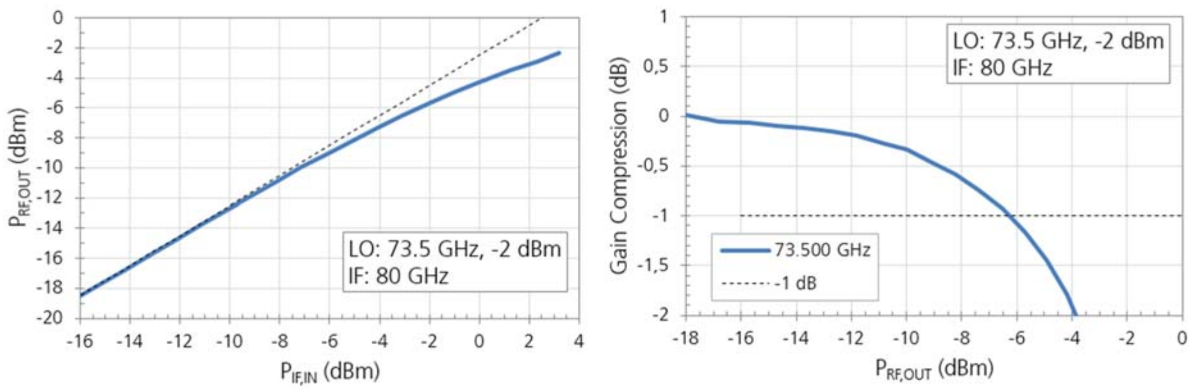


Figure 12: Measured RF-output power for different IF-input power levels (left) and gain compression vs. RF-output power (right). The LO frequency is 73.5 GHz and the IF frequency is 80 GHz.

Fig. 12 on the left shows the measured RF-output power vs. IF input power. The measurement was conducted at 73.5-GHz LO frequency and 80-GHz IF frequency. The corresponding gain compression vs. measured RF-output power level is depicted in Fig.12 on the right. The measured OP_{1dB} 1-dB gain-compression output power of the transmitter is around -6 dBm, which is around 3 dB lower than the on-wafer measured results reported in D4.3 [3]. This is mainly due to additional losses introduced by the 300-GHz MMIC-to-waveguide transition. In addition to that, the packaged MMIC was selected from a different wafer with improved yield and slightly reduced power density on device level. The corresponding IF-input power at 1-dB gain compression is –2 dBm.

6. 300-GHz Power Amplifier Module

Fig. 13 shows the functional block diagram of the 300-GHz PA module, which has been developed to further increase the output power level of the 300-GHz solid-state ThoR front end. The 300-GHz PA MMIC – which is described in detail in D4.3 [3] – has been packaged at Fraunhofer IAF into the M260 module series including a DC power supply for bias control and current sensing.

The required external positive supply voltage is in the range of 3.3 V to 5 V. The typical external DC current is around 350 mA. Hence, the resulting DC power consumption of the PA module is around 1.3 W for 3.6-V external supply voltage. The waveguide interface for RF is the H-band WR-3 waveguide, as described in D2.3 Specification of RF Design [1].

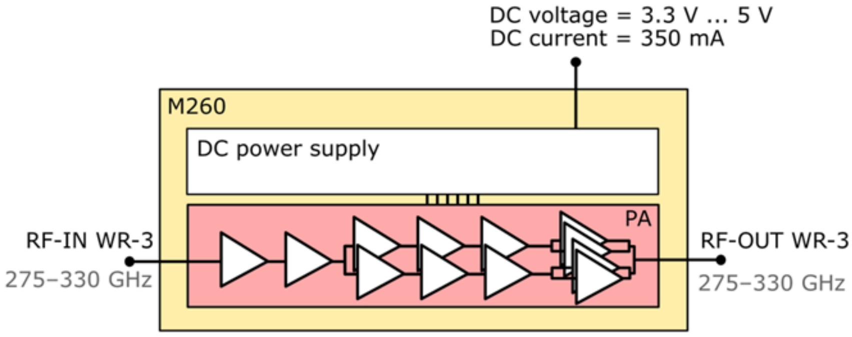


Figure 13: Functional block diagram of the 300-GHz PA module M260.

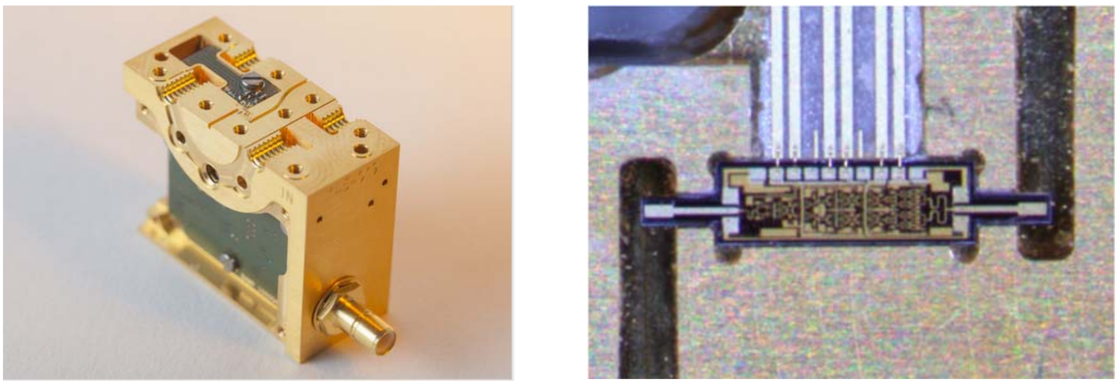


Figure 3: Photograph of the 300-GHz SSPA module and packaged PA MMIC.

Fig. 14 (left) shows the lower part of the split-block waveguide module and the close-up view of the package PA MMIC is depicted on the right in Fig. 14. In contrast to the RX and TX front-end MMICs described above, integrated MMIC-to-waveguide transitions are used, as described in detail in D4.3 [3]. These integrated transitions on 50-µm GaAs substrate typically provide reduced losses and improved return loss since no bond wires are required in comparison to the quartz transitions described in section 5. In contrast to the PA MMICs with 16-µm-finger-width CS devices in the output stage described in D4.3, however, the finger width in the employed final stage was reduced to 12 µm, in order to improve yield and bandwidth of the packaged PA MMICs.

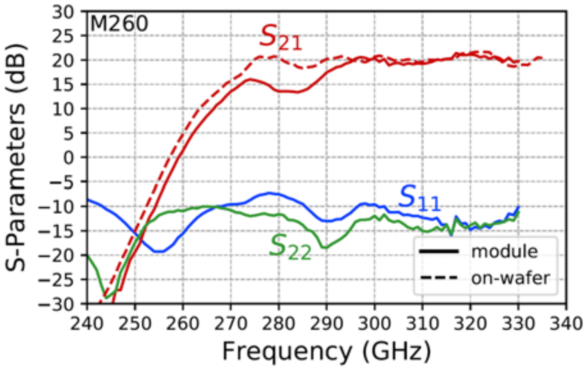


Figure 15: Measured S-parameters of the PA module. The dashed line represents the on-wafer measured S_{21} of the PA cell without integrated MMIC-to-waveguide transitions.

The S-parameters of the 300-GHz PA module are depicted in Fig. 15, measured up to 330 GHz. The on-wafer measured S_{21} of the stand-alone PA cell without integrated MMIC-to-waveguide transitions – which was measured on the same wafer – is also shown for comparison. In contrast to the on wafer measured S_{21}, the packaged PA MMIC shows a significant gain drop over the frequency range of 275–290 GHz. This drop is most probably caused by the MMIC-to-waveguide transition, which needs to be evaluated. Additional PA modules will then be packaged for the long range transmission which are planned in the ThoR project.

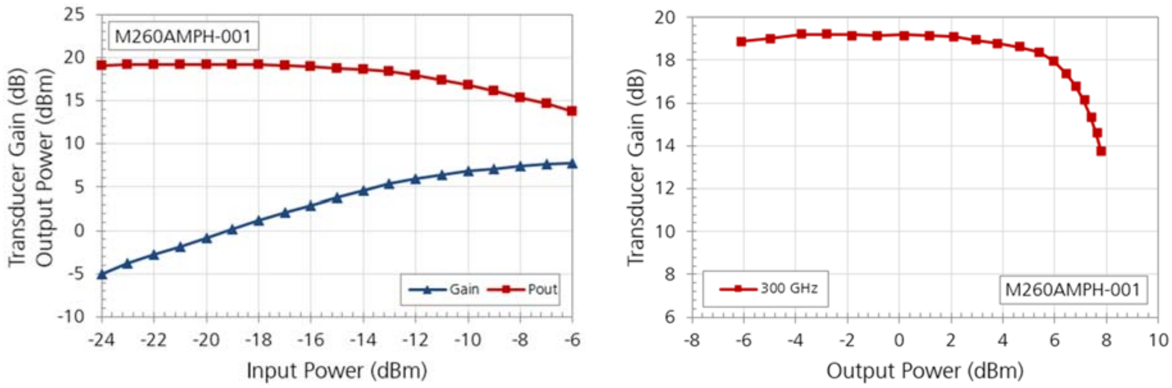


Figure 46: Measured transducer gain vs. measured input power (left) and measured transducer gain vs. output power (right) of the PA module.

The large-signal performance at 300 GHz of the PA module is depicted in Fig. 16, which shows the measured gain and output power vs. input power on the left as well as the measured gain vs. output power on the right. The measured saturated output power level is around 8 dBm, demonstrating good linearity with an OP_{1dB} 1-dB gain-compression output power level of 6 dBm.

7. Summary and Conclusion

This document describes the measured performance of the 300-GHz ThoR front-end and power amplifier modules, characterized using CW test signals.

The results of the front-end characterization in a laboratory environment are discussed in detail – considering the requirements in the context of the overall system implementation – and are summarized in the following:

- The 300-GHz receiver and transmitter Modules have been successfully packaged into waveguide modules, covering the IF-frequency range of 60 to 90 GHz for 70–75.5-GHz LO frequencies. The corresponding RF frequency band spans from 280 GHz to 310 GHz. Hence, the frontend modules cover the targeted 290–300-GHz frequency band targeted for channel aggregation in the ThoR project.

- The measured 300-GHz RX covers the 64–94-GHz IF frequency range with 4–7-dB conversion gain, representing a 3-dB bandwidth of at least 30 GHz. The lower IF-frequency band below 64 GHz, however, could not be measured with the W-band measurement setup which was used.

- The measured 300-GHz TX achieves output power levels above –4 dBm in saturation with an OP_{1dB} 1-dB compression output power of –6 dBm, covering a 3-dB RF bandwidth of 280 to 310 GHz.

- The measured 300-GHz PA module with 8-dBm output power in the targeted frequency range around 300 GHz. The measured small-signal gain over the 290–330-GHz frequency band is 20 dB, showing very good linearity with OP_{1dB} = 6 dBm.

Based on the verified performance of the 300-GHz front end and power amplifier, the planned ThoR live link implementation will proceed in WP6. After the above described single-tone measurement and verification, the front ends are currently being tested in back-to-back configuration in laboratory environment at the University of Stuttgart, using commercially available electronically generated LO signals, before gradual system integration with the other ThoR components in the planned WP6 live link demonstrations.

8. 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

[3] L. John, I. Dahn and I. Kallfass, "D4.3 RF Circuits Measurement Report", Jan 2020.

[4] A. Tessmann *et al.*, "A Broadband 220--320-GHz Medium Power Amplifier Module", CSICS 2014.