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

ThoR

Deliverable D4.6

Full RF-front-end test

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PU	**Public**	**X**
PP	**Restricted to other programme participants (including the Commission Services)**	
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)**	

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Change register

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Reviewed by	Dominik Wrana	USTUTT	Version A
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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: Guillaume Ducournau, Pascal Szriftgiser ULIL

2. Abbreviations (TO BE UPDATED)

AWG	Arbitrary Waveform Generator
BW	Bandwidth
Gbps	Giga bits per second
FWG	Flexible WaveGuide
InGaAs	Indium Gallium Arsenide
LNA	Low Noise Amplifier
LO	Local Oscillator
MPA	Medium Power Amplifier
NF	Noise Figure
PA	Power Amplifier
PSG	Performance Signal Generator
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature phase shift keying
RF	Radio Frequency
SHM	Sub-Harmonic Mixer
SNR	Signal to Noise ratio
SSPA	Solid State Power Amplifier
TWTA	Travelling Wave Tube Amplifier

3. Executive summary

The TeraHertz end-to-end wireless systems supporting ultra-high data Rate applications (ThoR) project aims at providing a technical solution for back- and fronthauling operating in the 300 GHz frequency range. These high frequencies offer the advantage of a high available bandwidth, which directly translates into high data rates. The ThoR system will be composed of modems in the standardized 60 and 70-80 GHz frequency bands and a high performance 300 GHz RF transmit/receive modules. These modules are fed by a local oscillator in in the 72-76 GHz frequency range.

The main focus of the D4.6 is to assemble the full RF Front-end developed in the THOR project. As targeted by the project, this RF Front-end is composed of three main elements:

- Photonics-based local oscillator, described in the D4.1
- RF modules for up/down conversion, and medium power amplification, described in D4.2, D4.3, D4.4.
- Travelling-wave tube amplifier, to increase the range of the system operating in the 300 GHz band, reported in the D4.5.

At the time of this report, considering the experiments carried out for the completion of the D4.6, the travelling-wave tube amplifier (TWTA) was unfortunately not yet available, even if a lot of progress were achieved during the project. Nevertheless, this is not a strict show-blocker for the validation of the overall THOR architecture, as the TWTA was intended to be used to extend the range of the transmission system.

In this report and experiments, the full assembly of the THOR RF front-end was realized using assembly of photonic LOs (two were developed for THOR), RF up-down converters and medium power amplifiers (MPAs). After characterization of single elements (MPA, up/down converters), the test of the transmitter and the receiver is realized towards the full assembly of the system required for DEMO parts. The tests are realized according to the target described in the DoW (up to QAM-16 32/40 Gbit/s).

4. Introduction

Although it is a big technological challenge, communication systems operating at extremely high frequencies, above 100 GHz, are experiencing an exponential development due to the continuously increasing demand for high data rates. Wireless links with centre frequencies around 300 GHz (so called terahertz band) have been successfully built in the last decade and impressive data rates have been reported in [1], [2] and [3]. Until now all these successful data transmissions have been realized in a laboratory environment transmitting only pseudo-random bits sequences. Also, almost all demonstrated systems are leveraging AWGs and complex digital signal processing (D.S.P.), which is interesting to evaluate the overall performances.

However, while future THz systems may not use this advanced D.S.P. processes, approaches that are compliant to real signals used in networks is of utmost importance. In addition, the target distance of the demonstrators in the ThoR project is up to km range rather than lab distances (10-15 meters).

In this context, the goal of ThoR project is to design and develop a terahertz (THz) communication system which can be used in real environments supporting a deployment of 5G and beyond 5G networks. Such communication system implies the combination of fast baseband and cutting edge terahertz devices. Fig. 1 shows the scenario of a real-life application in which the ThoR system can be successfully integrated. The main building blocks of ThoR communication device are modems, in orange, and the 300 GHz transmitter (TX) and receiver (RX), in green.

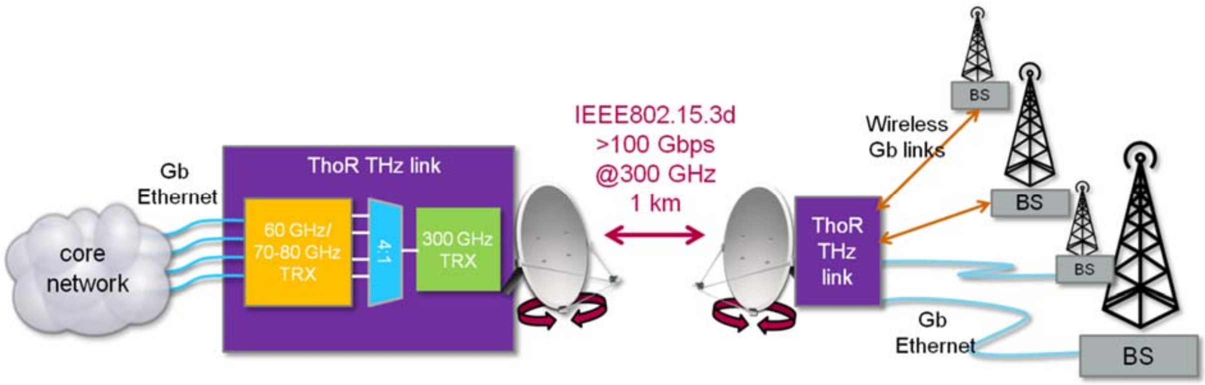


Fig. 1: The example of deployment scenario of the ThoR system. The ThoR communication device integrates baseband electronics, 60/70-80 GHz modems, 300 GHz RF transmit/receive modules (in green) and TWTA. [4]

The present deliverable is focused on the overall combination of the THOR developed hardware to reach the objectives that are up/down convertion of V/E bands signals to the 300 GHz range.

5. The photonic local oscillator (Photonic LO)

5.1. General overview – Overall RF Front end

The architecture of the overall RF front-end based on the combination of photonics-based LO, RF up/down converters and MPA is given in the figure 2.

In this overall architecture, the photonic-LO, after being multiplicated by 3, is mixed with IF input in V or E-band. Then the THOR up converter is used to reach 300 GHz band, before a final amplification stage using an SSPA or MPA. Then signal is sent to the THOR Rx, composed of LNA, mixer, also pumped by a second photonics-based LO, to down convert to IF-out.

In this configuration, a simplex link is realized. Duplex link is then achieved using a second set of Tx/Rx circuits, pumped per link terminal by the same photonic-LOs. In this approach, 2 photonic LO are used for duplex link (1 each site for the duplex link).

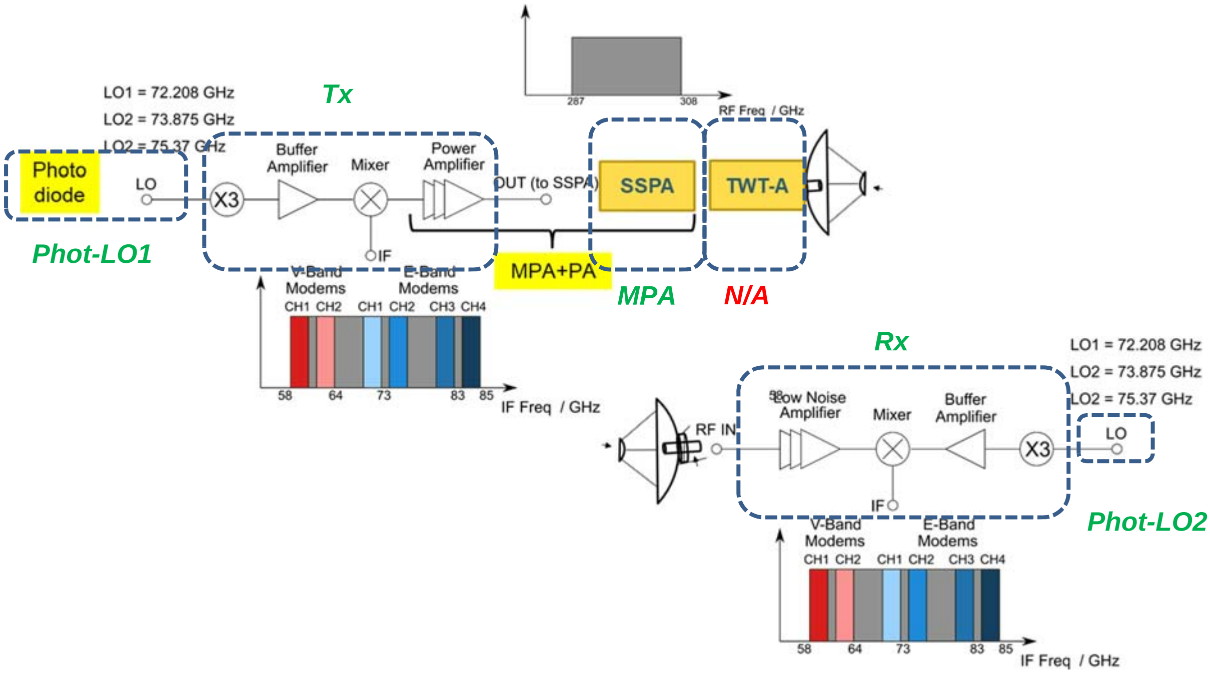


Fig. 2: Overall RF Front end of the THOR 300 GHz transmission system.

To validate the full RF front end, several tests have been carried out, for step-by-step validation of the different sub-systems. Especially, as the TWTA device will not be used in the final demonstrations, the test of the linearity of the MPAs handling data-modulated signals is one of the key points for the operational distance and system range.

Here the following characterizations are reported:

- Photonic LO system (Phot-LO1 or Phot-LO2)
- MPA linearity test (MPA, two devices available)
- Rx: THOR Receiver characterization: optimum photonic-LO driving power and optimum RF received power

- Tx: THOR Transmitter characterization: optimum photonic LO driving power and available RF output power

5.2. Photonic LOs (Phot LO1/2)

The typical performances of the photonic LOs were already reported on THOR D4.1. However, some changes were applied to photonic LO during the project, not affecting the performances. The following figure 3 is describing the configuration of the photonic LO.

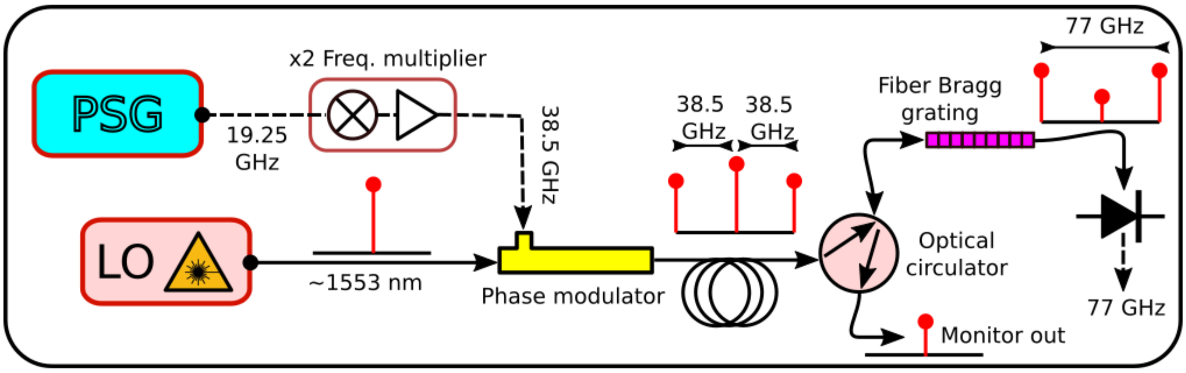


Fig. 3: Description of the Photonic LO realized by photomixing (example of 77 GHz LO generation).

The photonic LO is based on phase modulation of an incoming microwave signal from an electrical source (denoted as PSG, Performance Signal Generator on the figure). After a 2-times multiplication, a phase modulator is used to generate the spectral separation required for the photonic LO. Extraction of spectral lines is then realized using a Fiber Bragg grating, and a fast photodiode is converting the optical signal to mm-wave. Based on this, the phase noise of the photonic LO has been checked again and is given in the figure 4 hereafter.

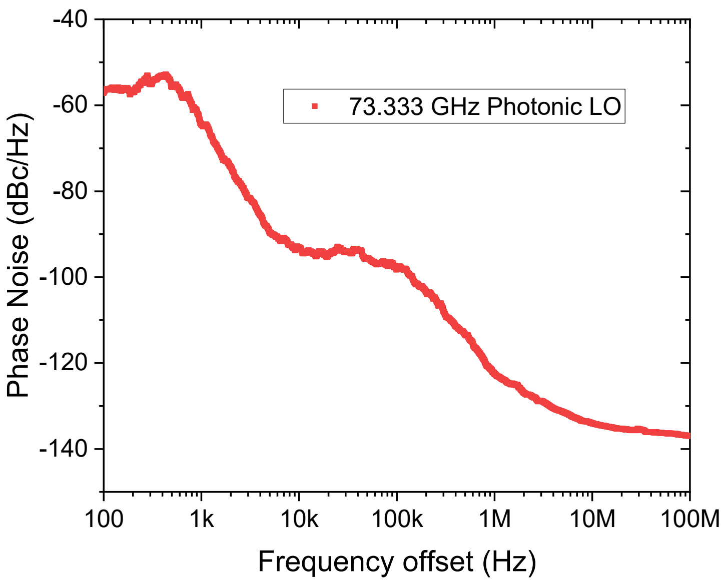


Fig. 4: Typical phase noise performance of the photonic LO at 73.333 GHz.

5.3. MPA linearity tests

In this paragraph, the linearity tests of the MPA are considered. In THOR, advanced modulation formats from MODEMs used at IF inputs and outputs required a high linearity of the overall system. Considering the losses associated to over the air transmissions at 300 GHz, the use of a final active stage is considered in the THOR link to meet the required link budgets.

In order to assess the use of this MPAs using modulated signals, a linearity assessment has been done, in continuous wave (CW) first then using modulated 300 GHz signals at MPA input to assess impairments after amplification stage.

a. CW analysis

In this first test a CW source is used to pump the MPA, where a reference curve is measured (Fig. 5), then output power after MPA is measured (Fig. 6).

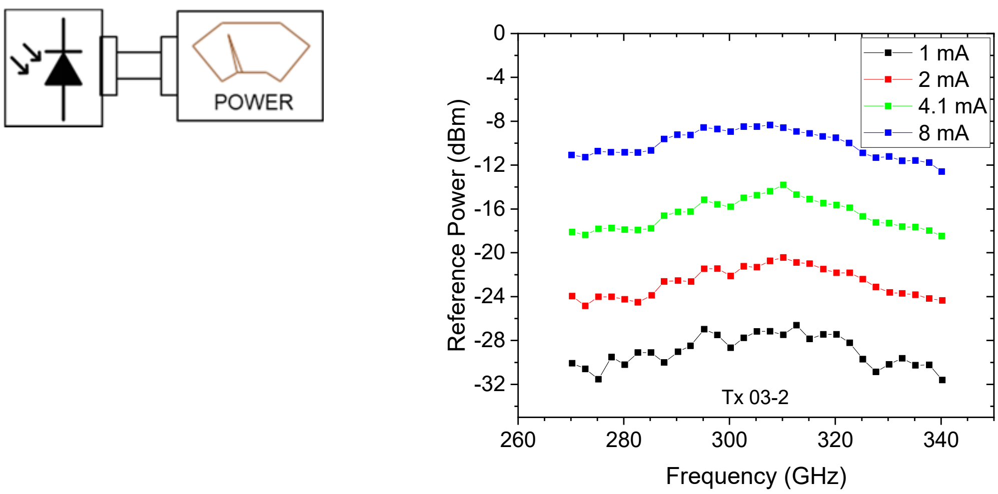
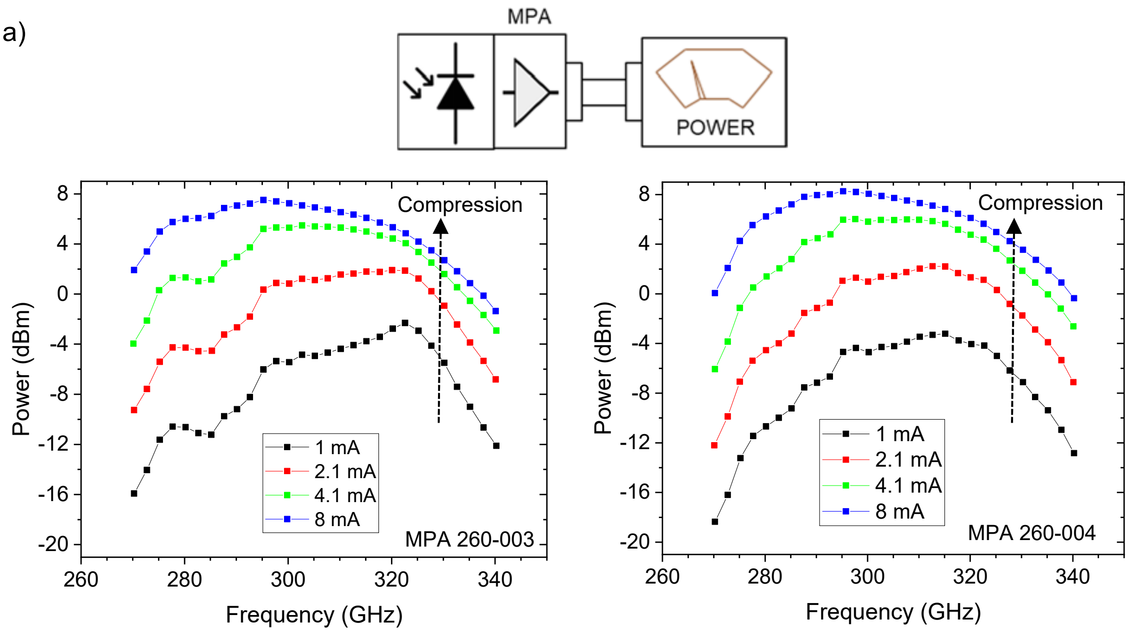


Fig. 5: Linearity test of the MPAs: reference curve using a photonics-driven signal generator.

a)



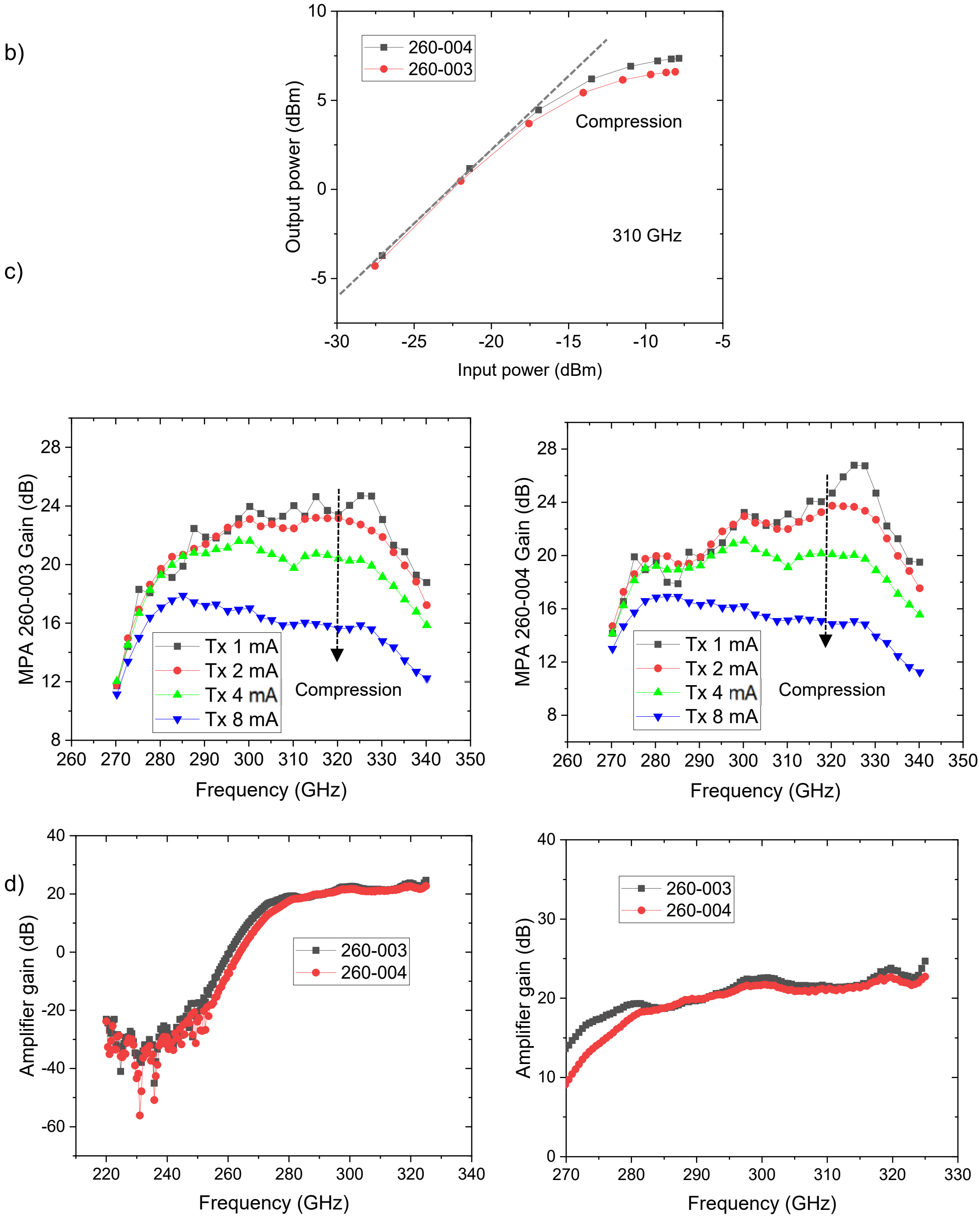


Fig. 6: Linearity test of the MPAs: reference (a) measurement of frequency-dependant output power for various input powers. b) Example of output power compression curve at 310 GHz. (c) is showing the frequency evolution of the MPA gains under several input powers, highlighting the saturation frequency dependant behaviour. For reference, the amplifier small-signal gain measured using VNA is shown in d).

All the power measurements where done using a PM5 power meter, which noise floor usually stands around -33 dBm. In the reference curve (Fig. 5), the power level of the reference source is acquired for several current levels, the output power being proportional to the squared current, ie an almost constant power shift of 6 dB is observed between references curves, confirming that the reference sources is operating in a linear regime to up -8 dBm (310 GHz).

After injection of this reference source in the MPA, output power is measured (Fig. 6). In this case, the frequency evolution of output power after MPA is evaluated. It was observed that saturation at MPA output occurs between red and green curves (Fig 6.c) which means that typically 2 dBm around 300 GHz is in the linear region for the MPA.

b. Modulated signal test of the MPAs

In order to confirm the linear behaviour of the MPAs using modulated signals, a second testbed was used to measure the ability of the MPAs to amplify a modulated signal.

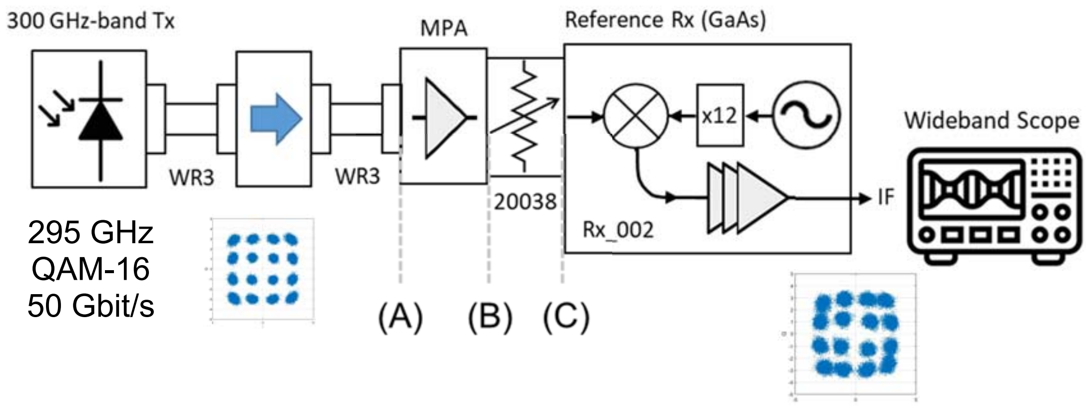


Fig. 7: Test of the MPAs using modulated signal at 295 GHz

In this testbed, a modulated signal is used, coupled with an isolator to feed the MPA, at 295 GHz (power performance shown in figure 8). First, a reference curve is measured by injecting the signal directly in a reference 300 GHz band receiver. This receiver is using GaAs technology, and is used to analyse the input modulated signal from the 300 GHz band Tx. This reference curve is shown in the figure 9. In this measurement, the power is kept constant at the input of the receiver thanks to the attenuator used in the front of the reference GaAs Rx. Then the two MPAs are used between isolator and reference receiver. In each case, the received power is kept constant at receiver level.

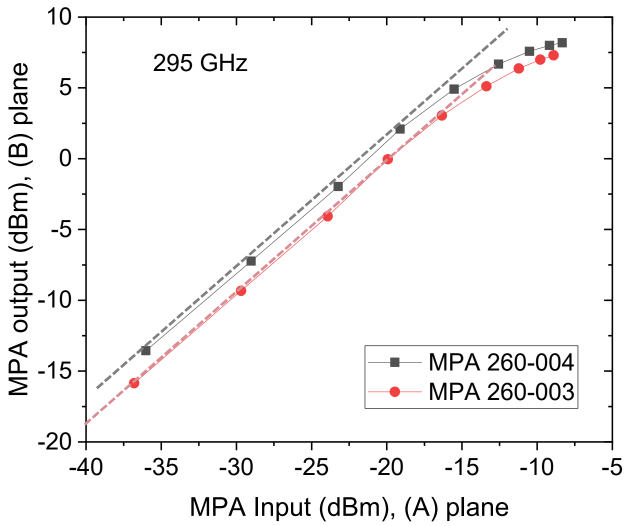


Fig. 8: Output power performance of the MPAs at 295 GHz. Linear behaviour is achieved up to ~2 dBm

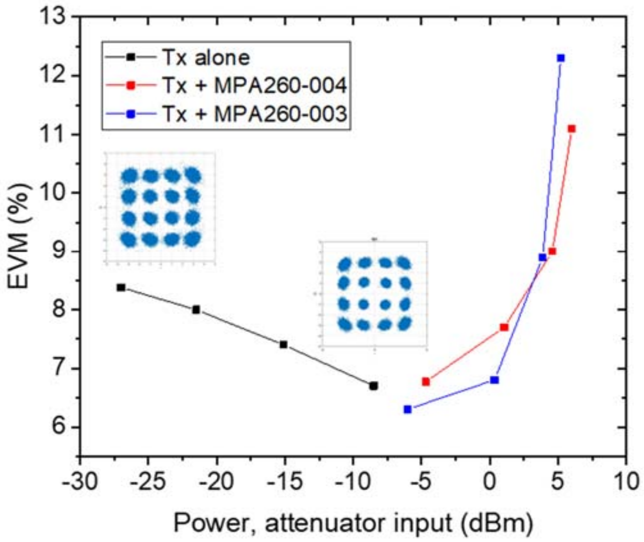
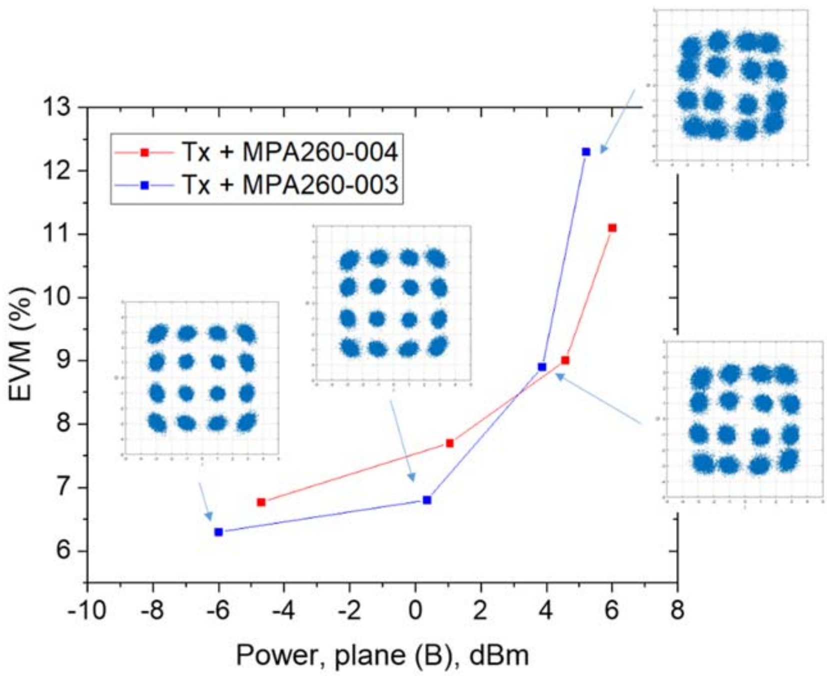


Fig. 9: Test of the MPAs using modulated signal: results comparing reference (Tx alone), and signal amplified by MPA (260-003 and 260-004 Thor modules tested).

Based on the EVM measured, the use of the MPA is clearly pushing forward the available power with a single Tx. However, it is observed that, beyond 2 dBm MPA output power, the EVM is degraded. This behaviour is in-line with the saturation observed at MPA output.



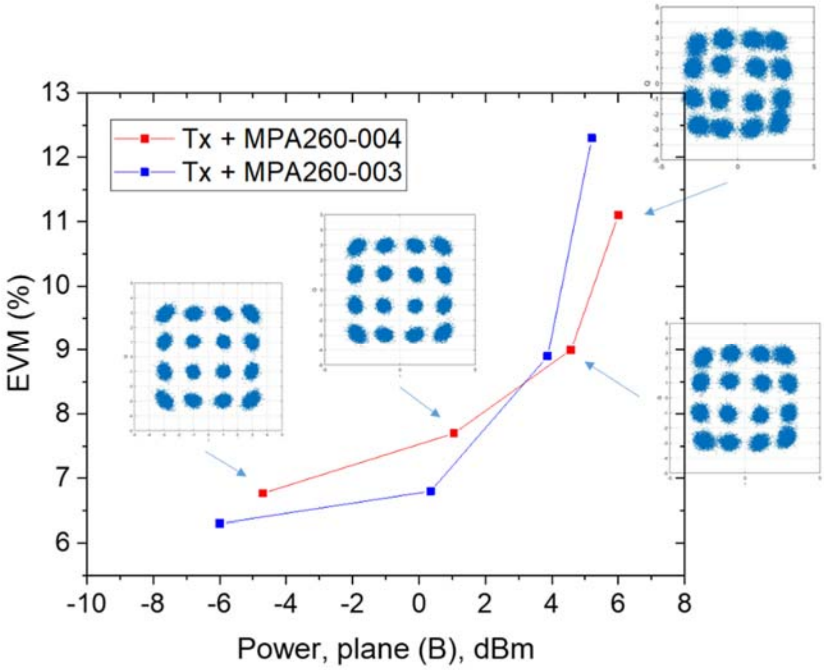


Fig. 10: Test of the MPAs using modulated signal: zoom on the EVM curves for MPA qualification. The EVM degradation and I/Q map degradation is observed for output MPA powers beyond 2-3 dBm.

As a conclusion on this part, it is estimated that using modulated data, output power of the MPA modules should not exceed 2 dBm to avoid any strong deterioration of constellations, which is around 6 dB back-off (Fig. 8). It is also worth to mention that stronger back-off should be taken into account if modulation format is more complex, e.g. QAM-32/64/128, as planned to be used in the MODEMS to be coupled to the full RF front-ends.

5.4. THOR Rx Validation & Test

In this part, the validation of the THOR receiver is targeted. In the THOR approach, the receiver and transmitter are pumped by a photonics-based LO. Here, the following experimental setup presented in the Fig 11 is used. In order to determine the optimum operating point of the THOR receiver, two tests have been conducted:

- Test of optimum driving power at LO port; in this case the photonic LO is used in combination with an external attenuator.
- Test of optimum received power (RF port): in this case, a modulated signal source (295 GHz) is used as a test-signal to feed the RF input with variable power.

In the THOR approach, the IF of the transmitter/receiver are designed to operate in the V and E-bands. Here, to assess the performance, as the IF output of the receiver is not directly recorded by available real-time oscilloscope (70 GHz bandwidth), an external down-conversion stage is used using a Schottky-based mixing. This enables to further analyse the IF signals with the real-time oscilloscope bandwidth.

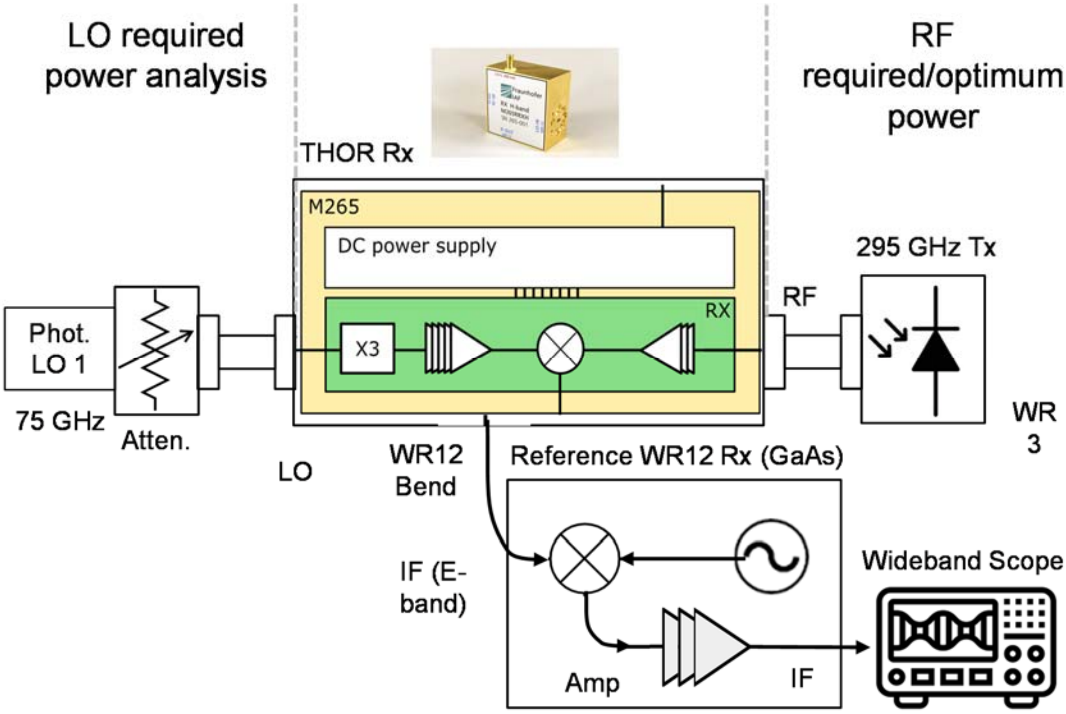


Fig. 11: Test of the THOR receiver (M265 assembly). Two types of test are targeted here: study of the pumping power (LO power analysis) and RF required power at Rx input.

LO required power analysis

In this part, we aim to determine the optimum feeding power of the the THOR receiver LO port. In this measurement campaign, the RF signal source at 295 GHz is fixed (constant power, -22 dBm), while the port is adjusted at LO port. Several modulation formats and data-rates were tested, from 8 to 15 GBaud. Figures 12 and 13 summarize the main results.

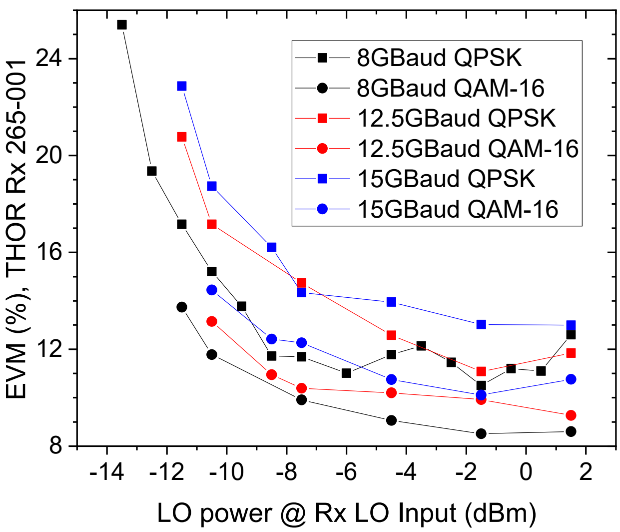


Fig. 12: Test of the THOR receiver: influence of the LO pumping power for several modulation formats and baud rates.

It was observed that the **required LO pumping power was on the order of -1~1 dBm**. At this power level, the EVM performance is in the saturated region, enabling to determine the required LO power to properly drive the receiver at the optimum LO region.

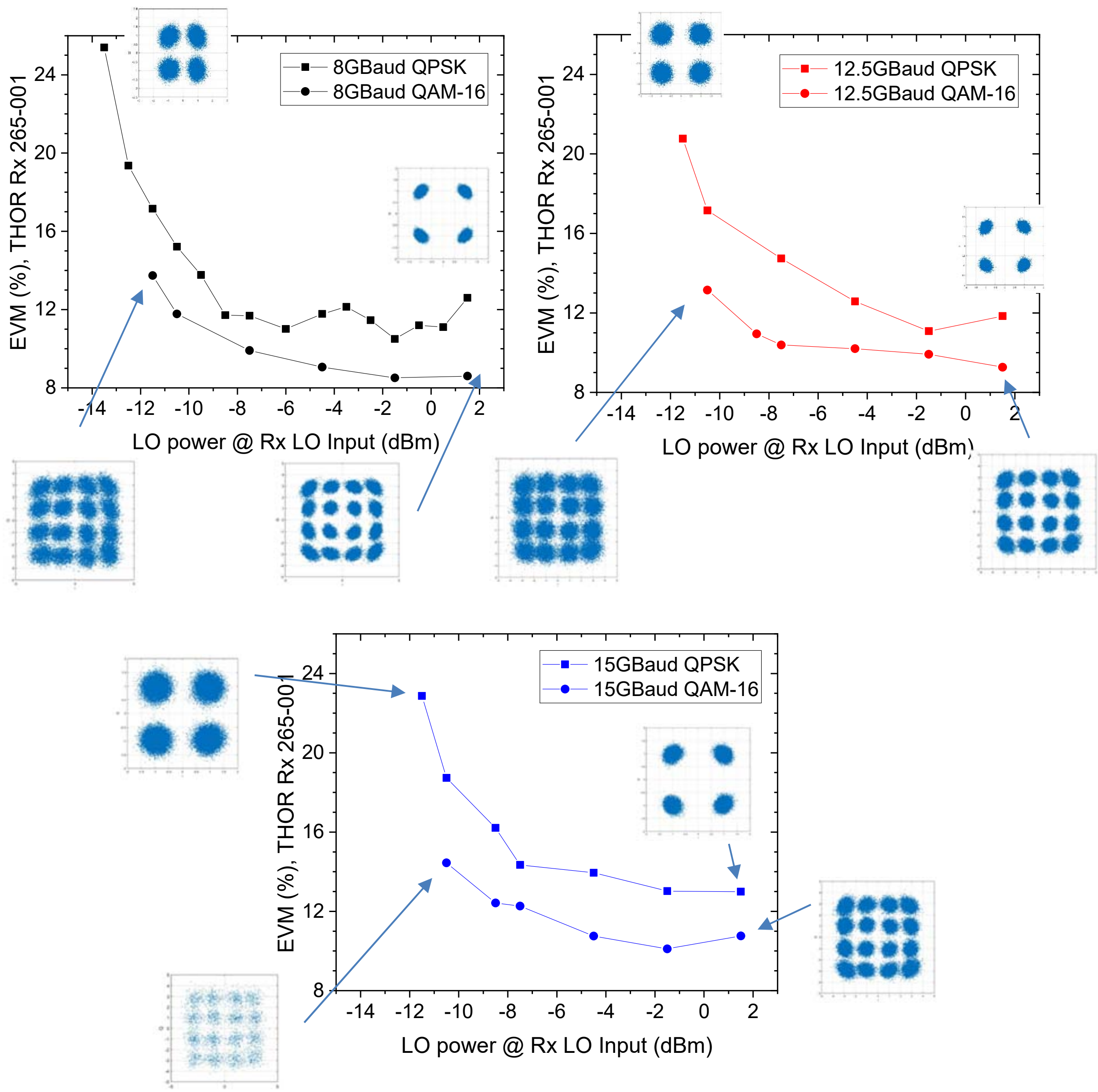


Fig. 13: Test of the THOR receiver: EVM performance with LO power using a constant Tx power around -22 dBm, baud rates used are 8, 12.5 and 15 GBaud, in QPSK or QAM-16.

RF required/optimum power analysis

Using the optimum LO pumping power (1.5 dBm), the RF power is adjusted to assess the optimum feeding RF power of the receiver. It was first checked that the transmitter used for the test was operating in the linear region. In order to confirm this a GaAs receiver operating at 300 GHz was used to detect the modulated signal. This receiver is the same than the one used during the linearity tests of the MPA stages (section 5.3 above).

The experimental setup to measure the reference curve (Tx feeding the GaAs receiver) is shown in the figure 14.

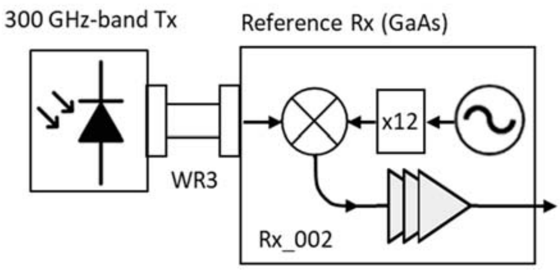


Fig. 14: Test of the THOR receiver: setup to measure the reference curve using a GaAs Schottky-based receiver in the 300 GHz band.

In the figure 15, the performance of the THOR receiver is given with various input powers at RF input and considering a QAM-16 signal at 50 Gbit/s. It is observed that the optimum operating point for the Rx operation is at -22 dBm. This is mainly due to the LNA saturation inside the receiver. Comparing with the GaAs Schottky reference Rx, the EVM performance is worse. This could have been expected because the reference Rx has no active stage at the input and the noise figure of the receiver is dominated by the SHM conversion losses. The presence of the LNA and the associated NF, higher that the SHM conversion losses is certainly impacting more for the THOR receiver case.

In the two cases, increasing the RF input power first improves the EVM, up to LNA saturation, and beyond -21 dBm an EVM degradation was observed. For the reference GaAs receiver, the EVM is getting better as power increases, thanks to the linearity of the whole Tx/Rx chain. From this result, we can conclude that the optimum RF input power is about -21 dBm, for this modulation/Baud rate set. As discussed earlier, higher modulation formats may degrade these values.

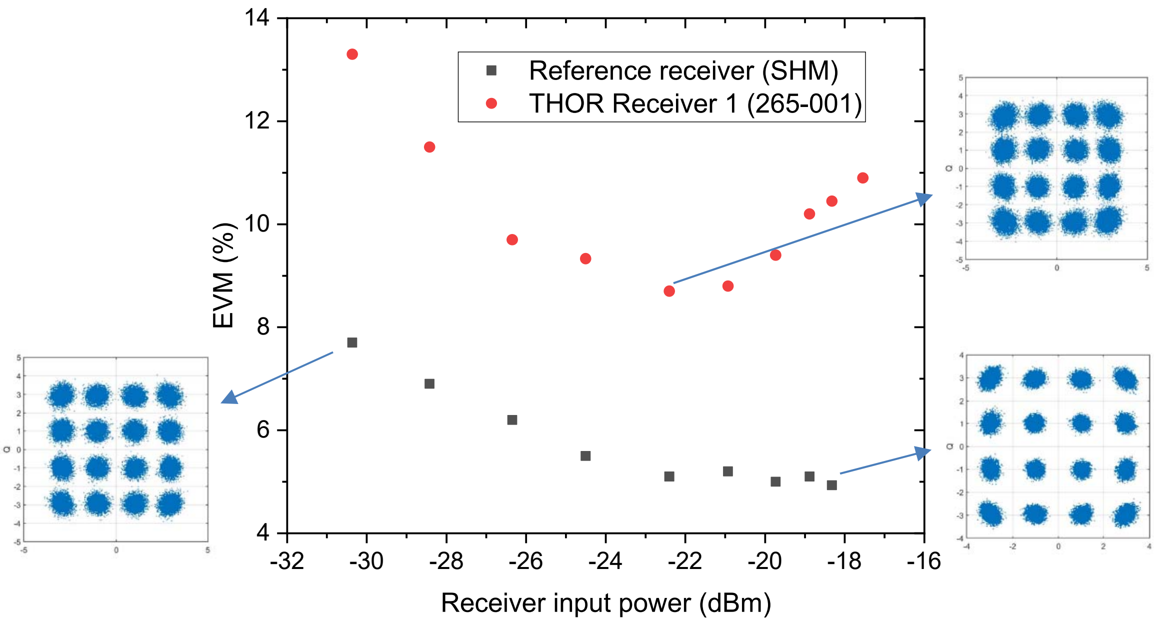


Fig. 15: Test of the THOR receiver: comparison of the reference GaAs receiver and THOR Rx 265-001 using a 295 GHz/50 Gbit/s input data source. IQ maps are shown for best and worse cases (Reference) and for optimum point (THOR receiver).

Initial estimation of the link budget

Based on the optimum point at receiver level (-21 dBm) and the available linear power of the MPA (estimated around 1-2 dBm), an initial link budget (system gain) of 22-23 dB (50 Gbit/s) can be expected with an association of the MPA/Rx. This initial estimation of available system margin will be detailled in the next sections.

5.5. THOR Tx Validation & Test

In this section the THOR Tx is tested. The test is conducted using an IF signal, upconverted in the 300 GHz band then detected using a reference receiver at 300 GHz. To do so, an IQ generator, operating as modulated signal source was used.

5.5.1. IF signal reference in the E-band

The I/Q generator used for E-band testing is combining a photodiode and amplifier. An attenuator is used to check the performance of I/Q generator as well as adjusting the power for THOR Tx testing.

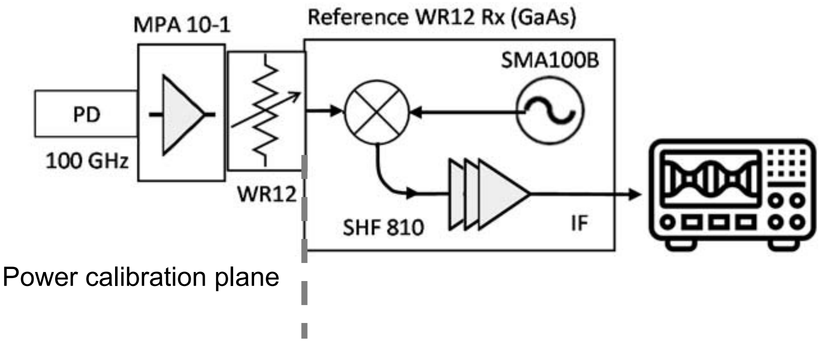


Fig. 16: Reference I/Q generator to enable the testing of the THOR Tx. IF frequency is set to 75 GHz.

First the power level of the I/Q generator is tested using a NRX 110 GHz power meter with WR10 adaptor for various WR12 attenuator positions. After that, a QAM-16 signal with a 8G baudrate was used as a test signal, the detection is done using the reference WR12 receiver. As can be seen the QAM-16 signal is characterized with a very low EVM, validating the I/Q generator. The optimum point, fixed by the reference receiver was around -25 dBm, for an attenuator position of 22 (relative unit). This attenuator position corresponds to a physical attenuation of 25 dB. Thus, at the MPA output (Figure 13), the available power can reach 0 dBm with a linear behaviour.

This power level is high enough and compliant for the testing of the THOR Tx as linear operation of the Tx is obtained for IF power input < -10 dBm.

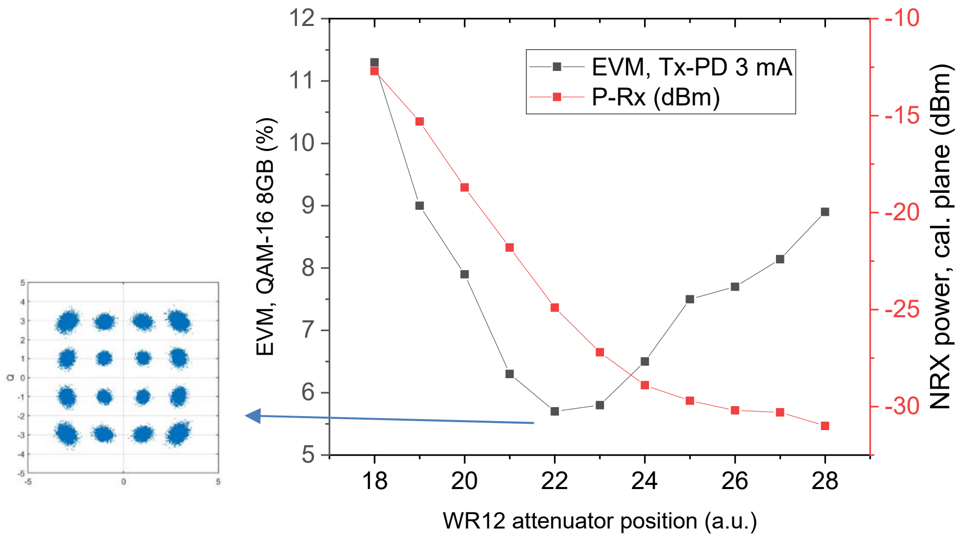


Fig. 17: Test of the reference I/Q generator: performance of the I/Q generator and reference receiver, in back-to-back configuration. IF frequency is set to 75 GHz. I/Q map is shown at optimum point.

5.5.2. Test of the THOR Tx

In this section the results of the test of the THOR Tx are shown. The I/Q generator validated in the last section was used an IF signal for the THOR Tx. The experimental setup to enable this test is presented on the figure 18. Here, the I/Q IF generator is settled at 75 GHz. The LO pumping frequency is set at 73.333 GHz. As a consequence, the THOR Tx output is at $3.F_{LO} + F_{IF}$ = 295 GHz.

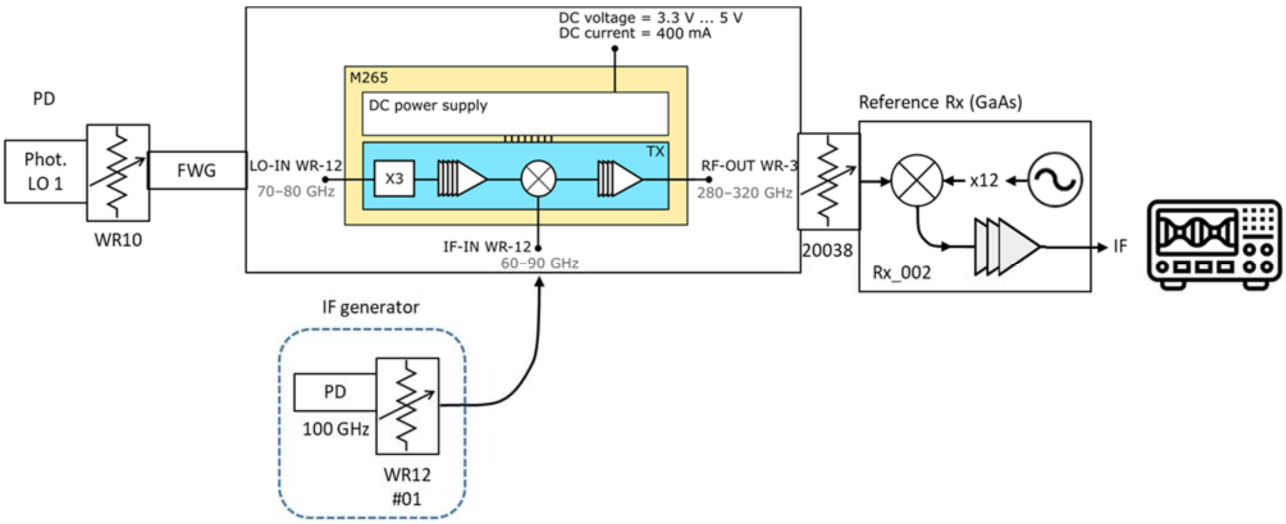


Fig. 18: Test of the THOR Tx using the reference I/Q generator: IF is 75 GHz, LO 73.333 GHz, and Reference GaAs Rx is used to down-convert the 295 GHz signal. FWG = Flexible Waveguide connection from Photonic LO to LO-In of the THOR receiver.

Influence of Tx LO power

As a first test, the LO power has to be tested to determine the optimum pumping power at LO port ("LO-IN" in figure 11) of the THOR Tx. In this case, the EVM performance was measured with a variable LO power, for an input IF power of -11 dBm (QPSK) and -13 dBm (QAM-16). Variation of the LO power was enabled by an attenuator. The result is shown by the figure 19.

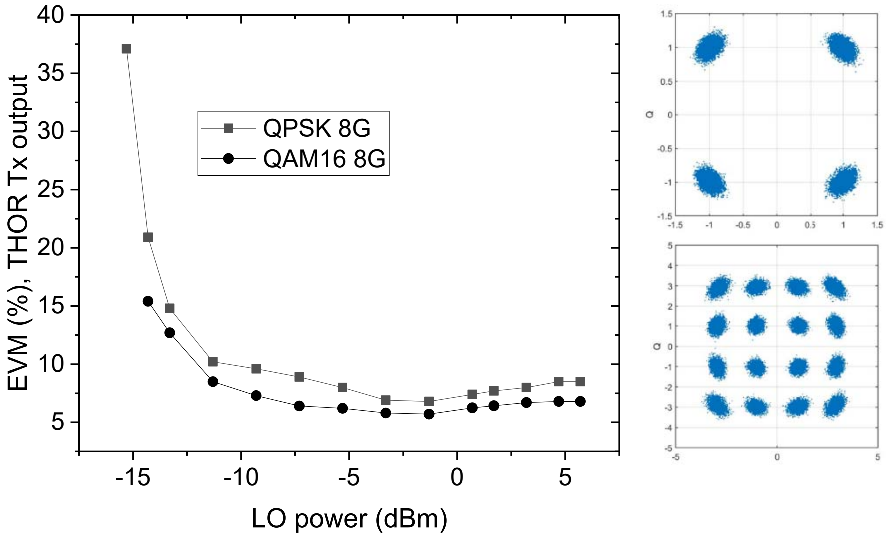
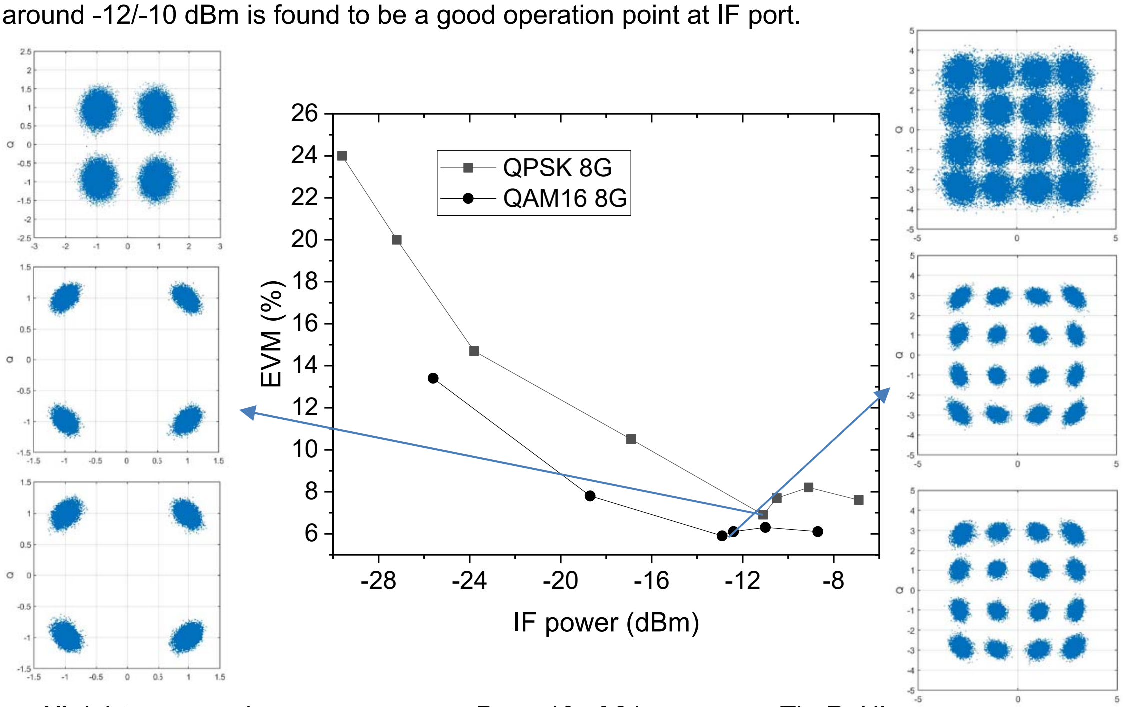


Fig. 19: Test of the THOR Tx: influence of the LO pumping power for 75 to 295 GHz up-conversion. IQ maps are shown at optimum LO power (16 Gbit/s for QPSK, 32 Gbit/s QAM-16).

Influence of Tx RF power

The second characterization test is to determine the optimum input power at IF port, using modulated signals. Two tests were done with 8 GBaud and 10 GBaud. The figure 20 summarizes the obtained EVM with IF power. Considering a linear response of the up-conversion, a power level around -12/-10 dBm is found to be a good operation point at IF port.



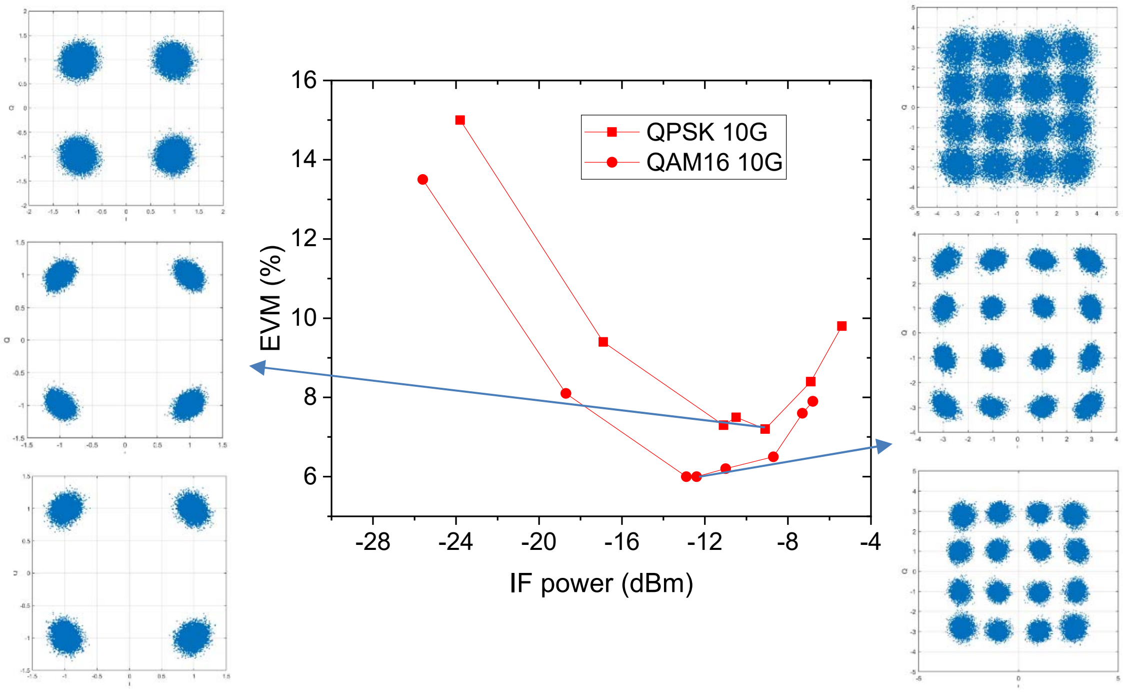


Fig. 20: Test of the THOR Tx: influence of the IF input power, IF is 75 GHz, output RF signal is 295 GHz. I/Q maps are set for worse EVM (up), optimum EVM (mid) and highest IF power (bottom), where non-linear effect is clearly set for QAM-16.

Conclusion of the test of the THOR Tx

As a conclusion, the optimum LO power observed is close to 0 dBm, and optimum IF input power close to -12/-10 dBm depending on the modulation format. However, it should be noted that in the final system, the MPA will be used at Tx output. Thus, as the MPA linear behaviour is validated up to around 2 dBm with a linear gain of about 20 dB, MPA input should stay < -18 dBm, which is clearly in the linear operation region of the THOR Tx.

Looking on the overall 8 GBaud IF to THz up-conversion, the EVM at IF input was 5.7/7.3 %, and 5.9/7% for QAM-16/QPSK. The impact of the up-conversion appears to be negligible, assuming that equalization is applied.

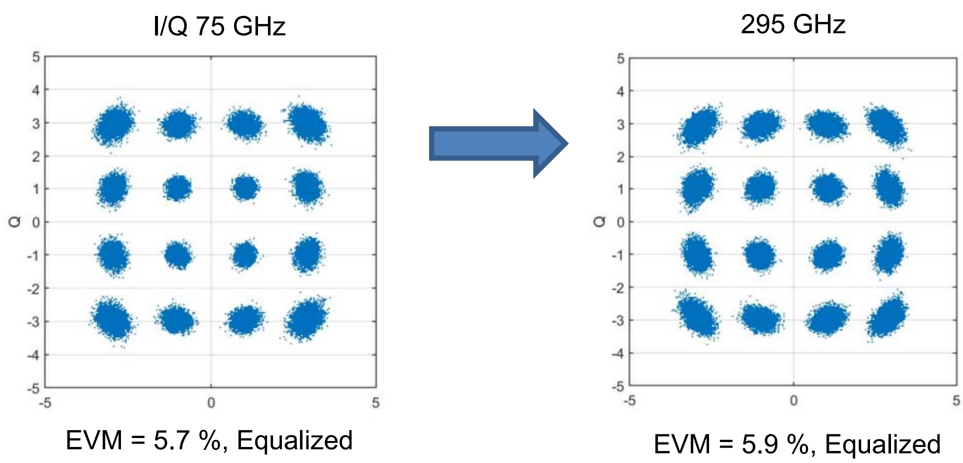


Fig. 21: Comparison of 8 GBaud QAM-16 reference, left (75 GHz) and up-converted (295 GHz). EVM obtained is very close.

6. Summary and conclusions

The general conclusion of this document is the validation of the different sub-systems that define the full THOR RF front end:

- The photonic LOs has been re-checked and are compliant to the requirements (phase noise and power performance).
- The THOR receiver was successfully pumped by the photonic LO. The optimum LO powers, RF power were determined using modulated data signals in the THz range, leveraging a dedicated setup established in Lille. The down-conversion of up to QAM-16/50 Gbit/s data-rate was validated, with EVM around 9%.
- The THOR transmitter was successfully pumped by the photonic LO. The linearity of the THOR Tx was determined and IF signals, up to 32 and 40 Gbit/s were successfully up-converted to the 300 GHz band. IF power optimum is found to be close to -12/-10 dBm (QAM-16). The degradation of the EVM from IF to THz band is found to be very low at the optimum point.
- The medium power amplifiers were tested in terms of gain, linearity in CW and degradation of the EVM with input modulated data was evaluated using several modulation formats and baud-rates. Available power at MPA output with no significant impairments on the EVM of the IQ map is found to be close to 1-2 dBm for QAM-16.

The next steps towards demo using the developed hardware is the Tx/Rx association, and validation of up/down conversion using a full chain. This work will be reported in the D6.4, dedicated on the DEMO 2 experiments carried out in laboratories (USTUTT and Lille), to validate the THOR systems prior to final outdoor DEMOs.

7. References

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