A Superheterodyne 300 GHz Transmit Receive Chipset for Beyond 5G Network Integration

Iulia Dan[#], Christopher Grötsch[#], Laurenz John[*], Sandrine Wagner[*], Axel Tessmann[*], Ingmar Kallfass[#]
[#]University of Stuttgart ILH, Stuttgart, Germany
[*] Fraunhofer IAF, Fraunhofer Institute of Applied Solid State Physics, Freiburg, Germany

***Abstract*— This paper presents a compact solid-state, fully integrated transmitter and receiver chipset operating at 300 GHz fabricated using a 35 nm gate-length InGaAs metamorphic high-electron-mobility transistor technology. Both circuits integrate a fundamental frequency converter. The local oscillator path consists of a multiplier by three and a buffer amplifier. The transmitter uses a power amplifier as an output stage for increased output power. The first stage in the receiver is a low-noise amplifier. The transmitter achieves a high linearity: The output-referred 1- dB compression point lies at -3 dBm. The receiver has a conversion gain of around 10 dB without any IF post amplification and an estimated noise figure of 7.3 dB. The absolute 3 dB RF bandwidth of the system is 42 GHz, ranging from 288 GHz to 320 GHz. The local oscillator input frequency can vary between 72 and 75.5 GHz. The particularity of this chipset is the very high and wideband IF frequency range, from 75 to above 91 GHz. This superheterodyne architecture and the compatibility to IF systems composed of wireless links developed in the frame of 5G enables the integration into a real network, bringing 300 GHz communication networks a step closer to being implemented in applications like front- and back-hauling.**

***Keywords*— 300 GHz wireless communication, broadband receiver, millimeter communication, submillimeter-wave monolithic integrated circuits (S-MMIC), metamorphic high electron mobility transistor technology (mHEMT)**

I. Introduction

While 5G technologies and products become a growing and important part of wireless networks worldwide, the importance of terahertz (THz) communication in future and beyond 5G networks cannot be denied. The need for higher bandwidths is a direct consequence of the constantly growing demand for higher data rates. THz communication poses many challenges, not only in terms of device availability. Packaging at these high frequencies is a big concern as well as the processing of analog information delivered by the integrated devices. This is the reason why most successful wireless transmissions above 250 GHz [1]–[4] are using solid-state circuits and were carried out in a laboratory environment, taking advantage of powerful signal processing tools.

[3] presents the first, and up to now only, application-ready prototype implementing 300 GHz devices for back- and front-hauling, involving the combination of THz transmission and standard single-mode fibers. We have proposed another implementation of THz communication in a real-world application in [5]. For this solution of a future front- and back-haul network a superheterodyne architecture is necessary. The combination of commercially available 5G communication systems operating in V- and W-Band and a 300 GHz frontend,

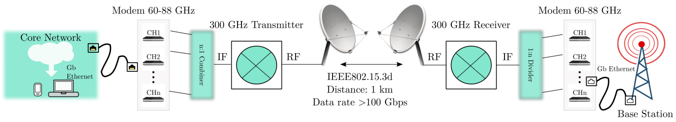

Fig. 1. Proposed solution for live integration of a 300 GHz frontend in a front- and back-haul network.

results in a wireless system compatible with the new IEEE 802.15.3d frequency standard [6], capable of being easily integrated in a live network. The work presented in [5] concentrates on the proof of concept for the proposed architecture and uses an existing radio frequency (RF) frontend designed for zero-intermediate frequency (IF) transmission. In this paper we are concentrating on the superheterodyne 300 GHz transmit receive chipset, with an IF operation range between 75 to 95 GHz. This chipset is the missing puzzle piece which completes the transmission experiment presented only as a proof-of-concept in [5].

II. Proposed Solution for Future Front- and Back-Haul Networks

The last portion of a communication network, the link between an edge cell and the core network, is realized at the moment by either wired or wireless links. The wired solutions are fast but very expensive and often impossible to deploy in remote areas. The future exponential growth of individual data rates means that the access cells have to be smaller and appear more frequently. The increasing number of cells will cause additional costs of optical fiber, which is already extremely high in an urban environment. Employing the solution pictured in Fig. 1 would provide the required capacity for this application. This system is based on a superheterodyne architecture and consists of two important components: the modem which provides the IF and the RF frontend. The modem communicates with the core network via Ethernet cable and realizes the first up-conversion to the frequency range between 60 and 88 GHz. According to the IEEE 802.15.3e-2017 standard [6] each modem channel can occupy up to 2.16 GHz of bandwidth. The IF can aggregate signals coming from one or more channels. The second up-conversion is realized by the 300 GHz transmitter. The RF signal is transmitted with data rates exceeding 100 Gbps using an antenna system over a variable distance up to 1 km to the base station where the 300 GHz RX and the modem down-convert the baseband signal.

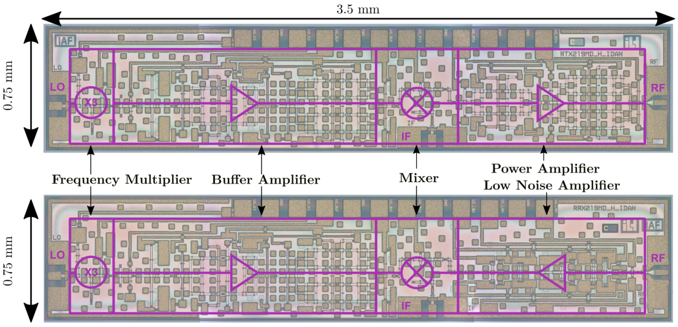

Fig. 2. Chip photographs of the fabricated transmitter and receiver MMIC.

Although 5G access networks extended the frequency spectrum above 6 GHz, where wireless transport links are currently operated, these products alone cannot support the beyond 5G requirements in large scale network deployment. In combination with a 300 GHz frontend like presented in Fig. 2 the ultra-high data rate demand can be satisfied. The 300 GHz transmitter and receiver presented in this work are based on millimeter-wave monolithic integrated circuits (MMICs) realized in a 35 nm gate-length InAlAs/InGaAs metamorphic high electron mobility transistor (mHEMT) technology. This mHEMT technology, described in detail in [7], is developed and optimized for high cut-off frequencies and ultra-low noise figure, featuring a transit frequency (f_T) of 515 GHz and a maximum frequency of oscillation (f_{max}) exceeding 1 THz.

The MMICs will be packaged into compact waveguide modules, similar to the ones presented in [4]. To enhance the maximum transmission distance different power amplifier modules can be connected after the 300 GHz TX like the one presented in [8].

The IF frequency is determined by the targeted application and ranges between 60 and around 90 GHz. Due to a frequency multiplier with a factor of three and a fundamental converter integrated on chip a local oscillator (LO) frequency in the range between 70 and 78 GHz is needed. The resulting RF range is between 270 and 320 GHz.

III. TX and RX MMICs

Fig. 2 shows the chip photographs of the integrated transmitter and receiver, both with a chip size of 0.75 x 3.5 mm. Both chips integrate a multiplier by three, a buffer amplifier and a mixer. Furthermore, the transmitter has a power amplifier as a last stage. A low noise amplifier is the first stage in the receiver.

The input frequencies in V-Band (40 to 75 GHz) are very convenient because of a good availability of off-the-shelf components. Additionally it is easier to generate a high input power for the multiplier in V-band rather than W-band (75 to 110 GHz) and higher. The frequency multiplier-by-.three operates in compressed class-A mode. The buffer amplifier is needed to provide enough LO input power for the up- and down-converter. It consists of five gain stages with four parallel transistors in the last two stages. The fundamental frequency converter uses one mixer cell based on one common source transistor. To achieve higher output powers a four-stage amplifier similar with the one used for the buffer stage is employed. To reduce the noise and make the down-converter suitable for THz communication a low noise amplifier (LNA) was designed and integrated in the receiver.

The DC power consumption of the transmitter is 357 mW, while the receiver consumes 281 mW. The difference is due to the lower power consumption of the LNA in comparison to the power amplifier. The overall functionality of the MMICs is verified by on-wafer measurements. The 300 GHz RF input signal of the receiver is synthesized using IAF in-house built frequency multiplier and amplifier modules. The LO signal around 70 GHz is generated using a commercially available frequency synthesizer with extension module and an IAF in-house built amplifier module. The same LO source is used for both transmitter and receiver. For the receiver the IF output signal at W-band frequencies is measured using a commercially available 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. For the on-wafer measurement of the 300 GHz transmitter MMIC, the IF signal is generated using a commercially available frequency synthesizer with extension module. In this case, the IF frequency band is limited to frequencies above 70 GHz. The 300 GHz output power of the TX MMIC is measured using a commercially available power meter. All measurements are calibrated on waveguide level and the known probe losses are deembedded.

Fig. 3 shows the measured output power of the transmitter, P_{out}, versus IF input power, P_{IF}, and the comparison to the simulation. This measurement is conducted for an LO frequency of 73.5 GHz, an LO input power of -2 dBm and an IF frequency of 75 GHz. The $P_{1dB,out}$ is measured to be at -3 dBm, while the simulated output-related compression point lies at 2 dBm. Hence, a difference of 5 dB can be observed between measurement and simulation. If a 10 dB back-off from the 1-dB compression point is considered, which would allow the transmission of complex modulation formats like 64QAM, a distance of around 80 meters could be covered. For the link budget calculation an antenna system consisting of a transmitter and a receiver antenna with a total gain of around 90 dBi. To increase the distance even further the usage of additional power amplifier modules like the one presented in [8] is necessary.

Fig. 4 shows the measured output power of the transmitter, P_{out}, versus IF frequency, f_{IF}, and the comparison with the simulation. This measurement is conducted with an LO frequency of 73.5 GHz, an LO input power of -2 dBm and four different IF input powers: -15, -10, -5 and 0 dBm. The IF frequency is limited by the setup to 75 GHz. Very good accordance between measurement and simulation is observed for low input power, below -10 dBm. For increasing input powers the difference between measurement and simulation increases up to around 4 dB for an IF input of 0 dBm. Overall, it can be concluded that the transmitter is very broadband with over 25 GHz of IF bandwidth. The exact bandwidth cannot be

Table 1. Comparison of state-of-the-art transmitter and receiver chipsets with an operation frequency above 250 GHz.

Ref	Technology	RF Frequency Range (3 dB limits) in GHz	BB / IF Frequency Range in GHz	TX OP_{1dB} in dBm	Receiver Noise Figure in dB	Power Consumption in mW
[9]	40 nm CMOS	260 - 270	0 - 20[1]	-5[2]	22.9	1790
[10]	80 nm InP-HEMT	272 - 302	2 - 32	-16	n.a.	n.a.
[11]	35 nm InGaAs mHEMT	270 - 314	0 - 22	-1	8.6	n.a
This work	35 nm InGaAs mHEMT	288 - 320	75 - 90	-3	7.3[1]	637

[1] according to simulation [2] estimation

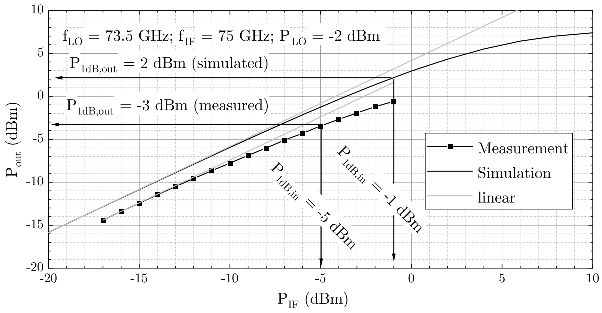

Fig. 3. Measurement results of the transmitted output power and comparison to simulation under the variation of the IF input power.

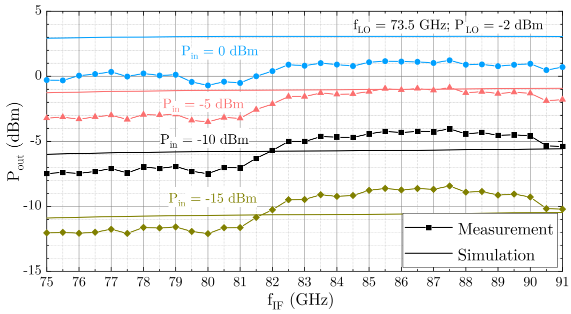

Fig. 4. Measurement results of the transmitted output power and comparison to simulation under the variation of the IF frequency.

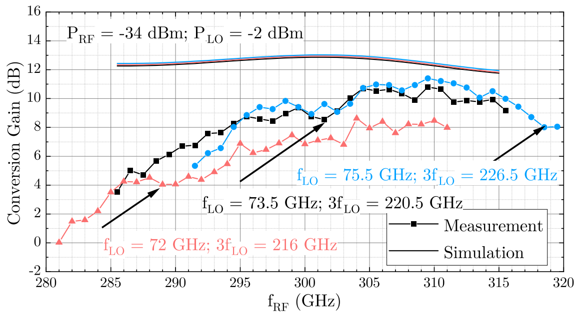

Fig. 5. Measurement results of the conversion gain of the designed receiver and comparison to simulation under the variation of the RF frequency.

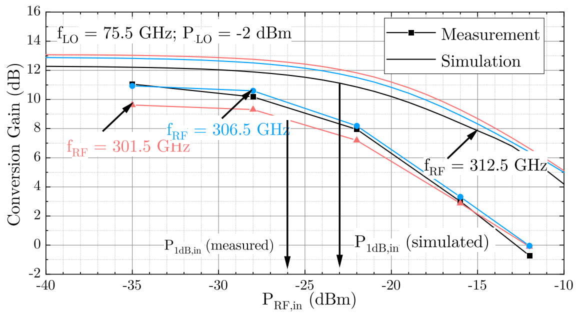

Fig. 6. Measurement results of the conversion gain of the designed receiver and comparison to simulation under the variation of the RF input power.

determined since it exceeds the measurement range.

For the integrated receiver similar measurements were conducted. The bandwidth of the receiver is dependent on the used LO frequency, as depicted in Fig. 5. For an LO of 72 GHz the 3-dB RF bandwidth calculates to 15 GHz, from 288 to 303 GHz. For an LO of around 73.5 GHz the maximum conversion gain is around 11 dB and the 3-dB RF bandwidth of 22 GHz between 293 and 315 GHz. The last measured LO frequency lies at 75.5 GHz. The possible measurement range for this LO frequency starts at only 291.5 GHz, limited by the measurement setup of the IF port. The 3-dB RF bandwidth covers the range from 295 GHz to 320 GHz. Compared to simulations, there is a good agreement, with deviations below 2 dB, for the LO frequencies of 73.5 GHz and 75.5 GHz in the RF frequency range between 303 and 313 GHz. Below 303 GHz and for the LO frequency of 72 GHz the deviation is higher, peaking at 8 dB for 285 GHz.

The linearity of the RX is plotted in Fig. 6. The measurement is 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 relatively constant deviation of 2 to 4 dB is observed between measurement and simulation. A maximum conversion gain of around 13 dB was simulated, while the measured conversion gain only reaches a maximum of around 9 dB for an RF of 301.5 GHz and 11 dB for the other two RF frequencies. The measured input-referred 1-dB compression point is 3 dB lower than the simulated one, at -26 dBm RF input power.

An important measurement which cannot be conducted on-wafer due to the lack of available sources is the measurement of the noise figure of the receiver. Considering the simulated noise figure of the LNA, the overall noise figure of the receiver can be calculated using Friis' formula and lies at 7.2 dB which corresponds to measurements of similar circuits in that technology [12]. After the integration into a waveguide module, the noise figure can further degrade.

IV. Comparison to State-of-the-Art

Table 1 shows the comparison to the state-of-the-art transmitter and receiver chipsets operating above 250 GHz. For this comparison all solid-state technologies that allow operation at these frequencies and the best performing chipset of the technology have been considered.

The MMIC chipset presented in this work is the only one operating with an IF input frequency above 75 GHz, supporting a superheterodyne transmission. This works exceeds the state of the art not only by architecture choice, but also by the lowest power consumption, a topic that gains more and more importance in the discussion about future networks. Although low-noise measurements cannot be conducted due to the lack of available sources, the receiver is expected to have a very low noise figure, similar to other 300 GHz receivers fabricated with the 35 nm InGaAs mHEMT technology [12]. In terms of linearity, especially important for the transmitter, measured by the output-referred 1-dB compression point, the presented TX MMIC is close to the state-of-the art. Only the transmitter fabricated in the same technology [11] shows a slightly better performance. Furthermore, the presented MMIC chipset operates at the highest reported RF range.

V. Conclusion

This paper presents a transmit and receive chipset fabricated in a 35 nm InGaAs mHEMT technology. The MMICs integrate a frequency multiplier by three, a buffer amplifier, a frequency converter and an RF power amplifier or a first RF low-noise amplifier. The LO input frequency lies between 72 and 75.5 GHz, the 3-dB bandwidth of the IF frequency is measured to exceed the range between 75 to 95 GHz and the RF frequency centers around 300 GHz, depending on the combination of LO and IF frequency. The superheterodyne transmission scheme allows the combination of wireless links developed in the frame of 5G, operating at frequencies above 60 GHz, with the RF system composed of the presented TX and RX. The proposed solution enables the integration of THz communication into a live application. The TX-RX chipset shows state-of-the-art high frequency performance in terms of bandwidth and linearity, and is therefore a promising candidate for future wireless high data rate communication systems in the lower THz band around 300 GHz.

Acknowledgment

The authors acknowledge and thank their colleagues from the Fraunhofer IAF epitaxy and technology department for their contributions during wafer growth and MMIC processing. This work has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation, under grant agreement No. 814523. ThoR has also received funding from the National Institute of Information and Communications Technology in Japan (NICT).

References

[1] H. Hamada, T. Tsutsumi, H. Matsuzaki, T. Fujimura, I. Abdo, A. Shirane, K. Okada, G. Itami, H. J. Song, H. Sugiyama, and H. Nosaka, "300-ghz-band 120-gb/s wireless front-end based on inp-hemt pas and mixers," *IEEE Journal of Solid-State Circuits*, vol. 55, no. 9, pp. 2316–2335, sep 2020.

[2] S. Lee, S. Amakawa, T. Yoshida, Y. Morishita, Y. Kashino, S. Hara, and M. Fujishima, "300-ghz cmos-based wireless link using 40-dbi cassegrain antenna for ieee standard 802.15.3d," in *2020 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT)*. IEEE, sep 2020, pp. 136–138.

[3] C. Castro, R. Elschner, T. Merkle, and C. Schubert, "100 gbit/s terahertz-wireless real-time transmission using a broadband digital-coherent modem," in *2019 IEEE 2nd 5G World Forum (5GWF)*, Sep. 2019, pp. 399–402.

[4] I. Kallfass, I. Dan, S. Rey, P. Harati, J. Antes, A. Tessmann, S. Wagner, M. Kuri, R. Weber, H. Massler, A. Leuther, T. Merkle, and T. Kürner, "Towards MMIC-based 300 GHz Indoor Wireless Communication Systems," *IEICE Transactions on Electronics*, vol. E98-C, no. 12, pp. 1081–1090, Dec 2015.

[5] I. Dan, G. Ducournau, S. Hisatake, P. Szriftgiser, R. Braun, and I. Kallfass, "A terahertz wireless communication link using a superheterodyne approach," *IEEE Transactions on Terahertz Science and Technology*, vol. 10, no. 1, pp. 32–43, Jan 2020.

[6] *IEEE Standard for High Data Rate Wireless Multi-Media Networks Amendment 2: 100 Gbps Wireless Switched Point-to-Point Physical Layer*, IEEE-SA Standards Board Std.

[7] A. Leuther, A. Tessmann, H. Massler, R. Losch, M. Schlechtweg, M. Mikulla, and O. Ambacher, "35 nm metamorphic HEMT MMIC technology," in *Indium Phosphide and Related Materials, 2008. IPRM 2008. 20th International Conference on*, May 2008, pp. 1–4.

[8] L. John, A. Tessmann, A. Leuther, P. Neininger, T. Merkle, and T. Zwick, "Broadband 300-GHz Power Amplifier MMICs in InGaAs mHEMT technology," *IEEE Transactions on Terahertz Science and Technology*, pp. 1–1, 2020.

[9] S. Lee, R. Dong, T. Yoshida, S. Amakawa, S. Hara, A. Kasamatsu, J. Sato, and M. Fujishima, "An 80 Gb/s 300 GHz-Band Single-Chip CMOS Transceiver," in *2019 IEEE International Solid- State Circuits Conference - (ISSCC)*, Feb 2019, pp. 170–172.

[10] H. Hamada, T. Fujimura, I. Abdo, K. Okada, H. Song, H. Sugiyama, H. Matsuzaki, and H. Nosaka, "100-Gb/s InP-HEMT wireless transceiver using a 300-GHz fundamental mixer," in *2018 IEEE/MTT-S International Microwave Symposium - IMS*, June 2018, pp. 1480–1483.

[11] I. Kallfass, P. Harati, I. Dan, J. Antes, F. Boes, S. Rey, T. Merkle, S. Wagner, H. Massler, A. Tessmann, and A. Leuther, "MMIC chipset for 300 GHz indoor wireless communication," in *2015 IEEE International Conference on Microwaves, Communications, Antennas and Electronic Systems (COMCAS)*, Nov 2015, pp. 1–4.

[12] A. Tessmann, A. Leuther, S. Wagner, H. Massler, M. Kuri, H. . Stulz, M. Zink, M. Riessle, and T. Merkle, "A 300 GHz low-noise amplifier S-MMIC for use in next-generation imaging and communication applications," in *2017 IEEE MTT-S International Microwave Symposium (IMS)*, June 2017, pp. 760–763.