Broadband InGaAs mHEMT THz Transmitters and Receivers

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Abstract:
We describe THz amplifier and front-end modules that have been developed based on an InGaAs metamorphic HEMT (mHEMT) technology for THz-wireless communication applications around 300 GHz, covering the frequency range between 270 and 330 GHz and enabling record output-power levels above 10 dBm. Furthermore, we report on the development of state-of-the-art distributed mHEMT circuits with absolute bandwidths in excess of 300 GHz as building block of next-generation ultra-broadband THz front ends.

1. Introduction

With the potential to realize wireless Tbit/s-throughput point-to-point (P2P) links, the upper millimeter-wave and lower sub-millimeter-wave frequency bands are intensively investigated for high-data-rate communication applications. Especially the THz frequency range around 300 GHz is receiving a lot of attention due to its potential to implement highly-broadband electronic transmit and receive circuits. To realize these wireless THz communication systems with real-time capability, different concepts have been demonstrated. In [1], e.g., the aggregation of several 2.16-GHz channels in a super-heterodyne architecture have been reported, in accordance with IEEE802.15.3d. In contrast to this channel-aggregation approach, a single broadband real-time modem—which was originally designed for 2x2 Polarization-MIMO digital-coherent fibre-optical transmission—is used in [2] to demonstrate the first real-time 100-Gbit/s THz wireless data link.

When using electronic THz front ends for the integration of fibre-optical and THz-wireless technologies in applications such as wireless fiber extension or high-capacity wireless backhauling, broadband integrated THz circuits are required. To this end, we report on highly-wideband state-of-the-art front-end and amplifier modules operating around 300 GHz. In addition, we describe recently developed ultra-broadband distributed amplifier and mixer circuits for next-generation THz communication applications. The monolithic microwave integrated circuits (MMICs) have been fabricated utilizing our InGaAs-channel metamorphic high-electron-mobility transistor (mHEMT) technology with 35-nm gate length [3]. These mHEMT devices feature a current-gain cutoff frequency f_T and power-gain cutoff frequency f_{max} above 500 and 1000 GHz, respectively, and provide record noise-figure values across the lower THz frequencies.

2. Broadband 300-GHz Front-End and Amplifier Modules

Due to the increasing transmission-line losses at the upper mm-wave and lower THz frequency range, integrated circuits are typically packaged into low-loss waveguide modules for the utilization of prototype wireless communication (or imaging) systems. As an example of high-performance THz waveguide modules that have been developed for wideband wireless communication application around 300 GHz, Fig. 1 shows the images of a 300-GHz transmit/receive module as wells as a 300-GHz high-power amplifier module. The assembly of the developed amplifier, frequency multiplier, and up-/down-converter MMICs is done using E-field-probe-based MMIC-to-waveguide transitions that are implemented on a low-loss fused silica substrate—connected to the circuits via short bond wires. For the split-block waveguide housing, plated brass is used.

The block diagram of the 300-GHz RX/TX module is depicted in Fig. 1 (a). The module contains seperate RX and TX InGaAs mHEMT MMICs with I/Q IF interface and an LO frequency around 100 GHz that is provided by an frequency-multiplier by 12 MMIC with 7.5–8.9-GHz input frequency. The transmit/receive module features a wide RF bandwidth exceeding 270 to 320 GHz with a linear output power of –10 dBm on the TX side. The targeted applications of the developed RX/TX modules (as well as similar 300-GHz InGaAs mHEMT front-end modules) that have been developed in recent years are channel sounding and the experimental investigation of wireless high-capacity THz P2P communication.

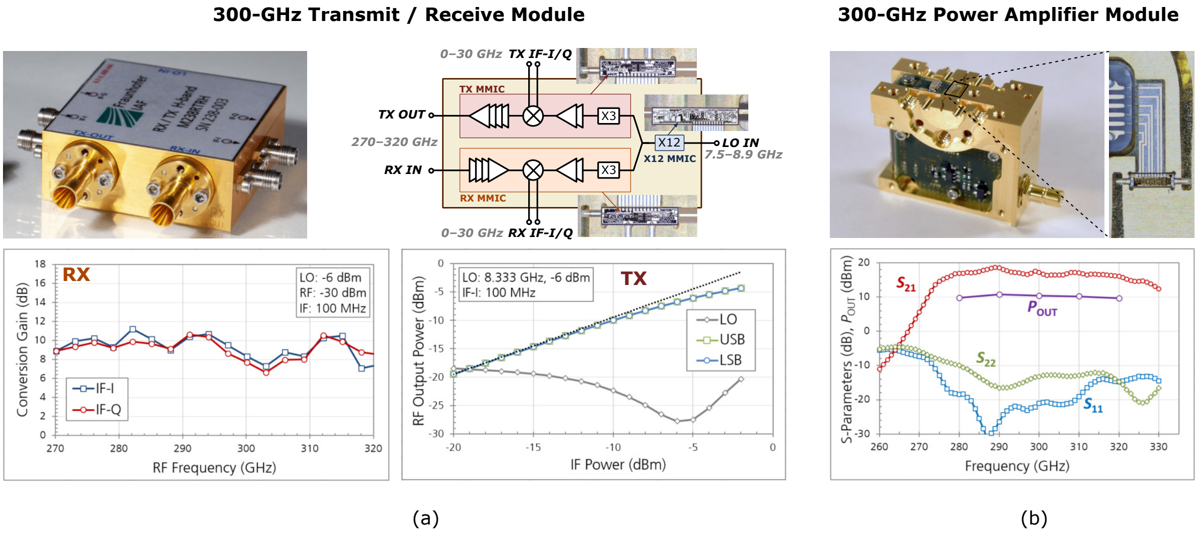

Fig. 1. (a) 300-GHz transmit and receive module and (b) 300-GHz power amplifier module.

To further increase the output power and provide the required power levels for real-world (mid-range) high-data-rate wireless P2P links, broadband 300-GHz InGaAs mHEMT high-power amplifier MMICs have been developed [4]. An assembled PA circuit, based on a 6-stage topology with cascode and common-source transistors, is depicted in the opened waveguide package in Fig. 1 (b). Using this amplifier module the output power of the transmitter can be increased to values above 10 dBm (10 mW), covering the frequency range between 275 to 330 GHz.

3. Ultra-Broadband Distributed Amplifier and Mixer MMICs

The reactively matched THz circuits and modules described above have been developed for wideband wireless communication application at the lower THz frequency band around 300 GHz, targeting an RF bandwidth in the range of 50–60 GHz between 270 to 330 GHz. While these MMICs with reactive on-chip matching networks can be designed with much larger RF bandwidth ($>$ 100 GHz bandwidth around 300 GHz, [5]), a significant gain in bandwidth can be achieved by utilizing distributed circuit topologies. To maximize the achievable bandwidth for a given transistor and wiring technology in distributed circuit concepts, the bandwith-limiting capacitances of the active devices (e.g. the input capacitance of the transistors) are compensated in artificial transmission lines.

As an example of the potential of distributed amplifiers (DAs) in the underlying InGaAs mHEMT technology, Fig. 2 (a) shows the chip fotograph as well as the mesured small-signal and noise performance of a 6-element DA with cascode unit cells [6]. The measured gain of this single-stage DA is 10 dB, extending over a record bandwidth larger than 300 GHz, and providing a low noise figure below 9 dB over this frequency range. Based on such a distributed unit-amplifier (UA) cell, distributed power amplifiers as shown in Fig. 2 (b) have been implemented. The depicted two-stage design consists of two parallel UAs in the output stage, featuring more than 10 dBm and up to 15 dBm of output power across the frequency range from 75 to 300 GHz.

To adress ultra-broadband wireless applications with $>$ 100 GHz of bandwidth, further distributed front-end building blocks such as distributed mixers (Fig. 2 (c), [8]) and distributed attenuators [9] have been designed, achieving state-of-the-art bandwidth for the respective circuit types. In addition, as frequency multipliers are another key building block of electronic THz front ends (even though the large LO bandwidth is more relevant for THz imaging applications), ultra-broadband distributed frequency multiplier topologies are currently investigated in the underlying InGaAs mHEMT technology. Utilizing the extremely-wide bandwith that can be achieved with these distributed amplification and frequency conversion circuits, new generations of ultra-wideband InGaAs mHEMT front-ends for wireless imaging and communication applications with up to and exceeding 200 GHz of absolute bandwidth are currently being developed.

4. Conclusion

With extremely-large absolute bandwidths, integrated THz circuits based on InGaAs mHEMT devices enable wireless THz front ends with channel bandwidths that are typically found in optical communication systems. The potential of such electronic THz front ends for new applications like hybrid fiber-optic/THz-wireless and high-capacity THz backhauling has been demonstrated with record data-tranmission experiments in recent years.

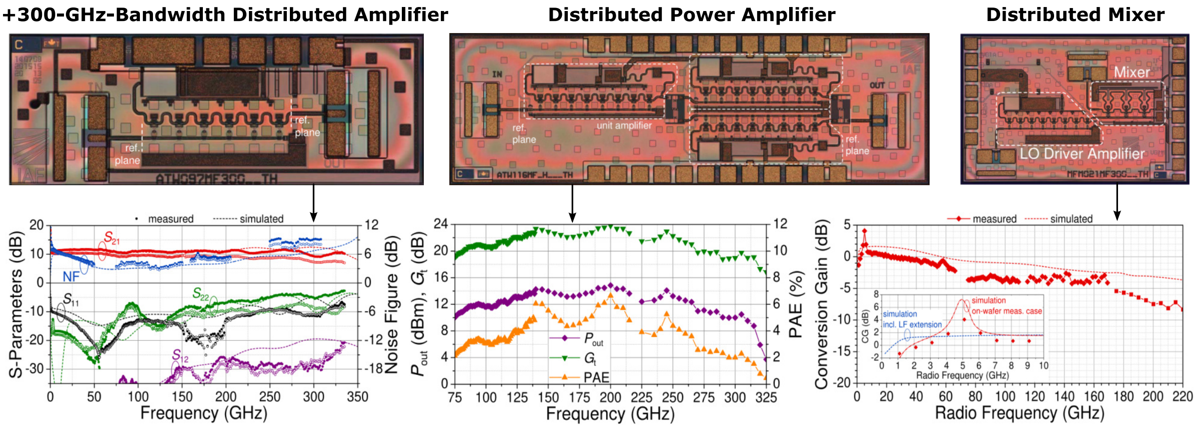

Fig. 2. Highly-broadband distributed circuits: (a) distributed amplifier with more than 300 GHz of absolute bandwidth, (b) distributed power amplifier with more than 10 dBm of output power over the frequency bands from 75 to 300 GHz, and (c) distributed mixer.

As described in this paper, recently developed state-of-the-art InGaAs mHEMT front-end and amplifier circuits that are adressing the lower THz frequencies enable broadband wireless communication applications with RF bandwidth in the range of 60 GHz, providing state-of-the-art noise-figure ($NF < 6$ dB) as well as output-power ($OP_{sat} > 13$ dBm) performance at 300 GHz. To even further increase the operating range of the THz front ends to absolute bandwidths above 200 GHz, distributed circuits and key front-end building blocks have been developed lately. Utilizing these distributed circuit concepts, amplifier circuits with a record bandwidth in excess of 300 GHz as well as highly-wideband power amplifiers, mixers, and attenuators have been reported—enabling the realization of next-generation ultra-broadband THz front ends for wireless Tbit/s communication.

5. References

References

1. D. Wrana, Y. Leiba, L. John, B. Schoch, A. Tessmann and I. Kallfass, ”Short-Range Full-Duplex Real-Time Wireless Terahertz Link for IEEE802.15.3d Applications,” 2022 *IEEE Radio and Wireless Symposium (RWS)*, Las Vegas, NV, USA, 2022, pp. 94-97, doi: 10.1109/RWS53089.2022.9719954.
2. C. Castro, R. Elschner, T. Merkle and C. Schubert, ”100 Gbit/s Terahertz-Wireless Real-Time Transmission Using a Broadband Digital-Coherent Modem,” 2019 *IEEE 2nd 5G World Forum (5GWF)*, Dresden, Germany, 2019, pp. 399-402, doi: 10.1109/5GWF.2019.8911673.
3. A. Leuther, A. Tessmann, M. Dammann, H. Massler, M. Schlechtweg and O. Ambacher, ”35 nm mHEMT Technology for THz and ultra low noise applications,” 2013 *International Conference on Indium Phosphide and Related Materials (IPRM)*, Kobe, Japan, 2013, pp. 1-2, doi: 10.1109/ICIPRM.2013.6562647.
4. L. John, A. Tessmann, A. Leuther, P. Neininger, T. Merkle and T. Zwick, ”Broadband 300-GHz Power Amplifier MMICs in InGaAs mHEMT Technology,” in *IEEE Transactions on Terahertz Science and Technology*, vol. 10, no. 3, pp. 309-320, May 2020, doi: 10.1109/TTHZ.2020.2965808.
5. L. John et al., ”A 280–310 GHz InAlAs/InGaAs mHEMT Power Amplifier MMIC with 6.7–8.3 dBm Output Power,” in IEEE Microwave and Wireless Components Letters, vol. 29, no. 2, pp. 143-145, Feb. 2019, doi: 10.1109/LMWC.2018.2885916.
6. F. Thome and A. Leuther, ”First Demonstration of Distributed Amplifier MMICs With More Than 300-GHz Bandwidth,” in *IEEE Journal of Solid-State Circuits*, vol. 56, no. 9, pp. 2647-2655, Sept. 2021, doi: 10.1109/JSSC.2021.3052952.
7. F. Thome and A. Leuther, ”A 75–305-GHz Power Amplifier MMIC With 10–14.9-dBm Pout in a 35-nm InGaAs mHEMT Technology,” in *IEEE Microwave and Wireless Components Letters*, vol. 31, no. 6, pp. 741-743, June 2021, doi: 10.1109/LMWC.2021.3058101.
8. F. Thome, S. Wagner and A. Leuther, ”A 1–170-GHz Distributed Down-Converter MMIC in 35-nm Gate-Length InGaAs mHEMT Technology,” in *IEEE Microwave and Wireless Components Letters*, vol. 32, no. 6, pp. 748-751, June 2022, doi: 10.1109/LMWC.2022.3162762.
9. P. Neininger, F. Thome, L. John, A. Leuther, S. Chartier and R. Quay, ”Ultra-Wideband mmW Digital Step Attenuator,” 2023 18th European Microwave Integrated Circuits Conference (EuMIC), Berlin, Germany, 2023, pp. 1-4, doi: 10.23919/EuMIC58042.2023.10288944.