A Superheterodyne 300 GHz Wireless Link for Ultra-Fast Terahertz Communication Systems

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Abstract — **This paper presents an all-electronic superheterodyne wireless system based on millimeterwave monolithic integrated circuits at a center frequency of 300 GHz. Superheterodyne operation is attractive for compliance with the recent IEEE802.15.3d frequency standard. The super-heterodyne transmission is realized, both, with mixers operating at a frequency of 10 GHz, and with an arbitrary waveform generator output centered around 10 GHz. The paper compares both options in terms of error vector magnitude for different baud rates and modulation formats. Data rates of up to 60 Gbps and distances of up to 10 meters are achieved using complex modulated signals like 16-QAM and 32-QAM.**

Keywords — **Submillimeter wave integrated circuits, Submillimeter wave wireless communication, Quadrature amplitude modulation, Constellation diagram.**

I. Introduction

Driven by the need of higher data rates, the interest for submillimeterwave communication systems has been growing rapidly in the past years. Numerous groups have achieved good results in this field of research. Data rates of more than 100 Gbps have been reported using both all-electronic technologies [1], and photonics [2]. The reached data rates show that the terahertz range around 300 GHz is a viable solution, that can satisfy the increasing need for wireless data. A recognition of this fact is the new IEEE 802.15.3d Standard [3], which allocates the frequency range from 252 to 325 GHz to future wireless communication networks, such as backhauling, fronthauling, last-mile access, ad-hoc networks for big events or in dense urban areas, smart offices and data centers. The key to the transition from laboratory experiments to real applications is the integration of existing 5G technologies into new communication systems. Already established 60 GHz wireless modems as well as new yet to be developed systems in the lower millimeter-wave range, below 100 GHz, can be combined with high-end submillimeterwave wireless links to provide the bandwidths that can cope with the increasing demand of capacity requirements. This paper presents a superheterodyne 300 GHz wireless system, combining commercially, accessible baseband technology with a state-of-the-art high-end submillimeterwave link, inline with the new THz frequency standard.

II. The superheterodyne concept

Although many technical challenges like DC offsets and carrier leakage are involved, wireless links in the 300 GHz range and above use exclusively direct up- and down-converters, which implies the usage of fast digital processing equipment both in the generation part, arbitrary waveform generators (AWG) as well as in the receiving part, real-time oscilloscopes. Typical analog to digital converters used in 300 GHz transmission experiments have bandwidths up to 40 GHz and in this way the advantage of the unallocated band and of the high available radio frequency (RF) bandwidth can be fully used and high data rates can be achieved. Looking a step further into the integration of these wireless systems in applications like front- and backhaul, smart offices or data centers, the usage of expensive high bandwidth AD converters becomes unfeasible. The randomly generated data transmitted up to now in the 300 GHz links needs to be replaced by real-time data. The transition to cost effective, largely available baseband solutions requires the usage of a superheterodyne system, where high data rates are reached by means of channel aggregation. A parallelization of modems, up-converted in the 300 GHz band, enables the wireless high data rate transmission of real-time data, bringing terahertz communication a step closer to real life application.

In this paper we present two possibilities of realizing the superheterodyne architecture. The usage of an AWG which generates the intermediate frequency by applying a carrier offset to the desired data, validates the concept and the potential of the system. The second one uses commercially available mixers, which work as direct up- and down-converters, to generate the IF input and output for the 300 GHz transmitter and receiver.

III. System Components and Measurement Setup

The 300 GHz system is composed of one transmitter (TX) and one receiver (RX), each based on one monolithic millimeterwave integrated circuit (MMIC) packaged in split-block waveguide modules with a WR-3 output at the RF port and a WR-12 at the local oscillator (LO) input. The MMICs are fabricated in a 35nm metamorphic high electron

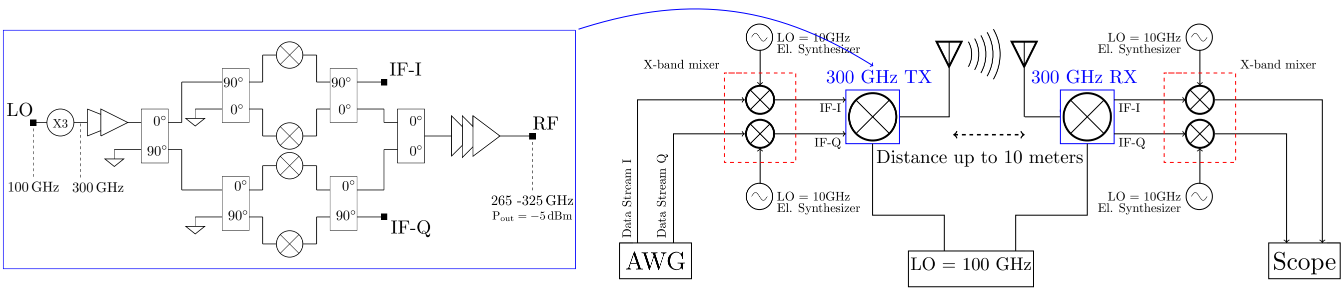

Fig. 1. Left-hand side: Schematic of the fully integrated 300 GHz transmitter MMIC. Right-hand side: Schematic of the terahertz superheterodyne wireless system composed of the RF circuitry: the 300 GHz transmitter and receiver and the baseband circuitry: the X-band mixers, with their respective LO path, for the generation of the intermediate frequency and the digital-to-analog and analog-to-digital converters.

mobility transistor (mHEMT) InGaAs technology described in detail in [4].

Fig. 1 shows on the left-hand side the schematic of the fully integrated transmitter MMIC. The input LO frequency of 100 GHz is multiplied by three in a frequency multiplier to reach the overall LO frequency of 300 GHz. A buffer amplifier assures that the power level of the LO signal is enough to drive the mixer into saturation. A fundamental, passive, single balanced, IQ mixer is used as up-converter. The IF signal is provided to the mixer cells via the isolated ports of the tandem couplers. The RF signal is post-amplified in an integrated power amplifier. In the receiver (RX) the RF signal is pre-amplified by a low noise amplifier and down-converted by the same mixer as in the transmitter. The components in the LO path, the multiplier by three and the buffer are identical in the transmitter and in the receiver. The modules have been characterized using single tone signals and the packaged transmitter achieves a saturated output power of $-5\,\mathrm{dBm}$ and the receiver has a maximum conversion gain of 10 dB.

The 100 GHz LO signal is provided by a separate waveguide module which integrates a frequency multiplier by twelve and a power amplifier. Therefore, an input frequency of 8.33 GHz is required. One frequency synthesizer provides this signal to both transmitter and receiver, thus the setup is coherent. Two horn antennas with 22 dBi gain are used to transmit the signal over 50 cm, which corresponds to an optimal RF input power of around $-42\,\mathrm{dBm}$ for the receiver, under linear operation conditions for the transmitter. To overcome even higher distances and to prove that the system is suitable for indoor applications like smart offices, additional collimating dielectric lenses are added in front of the horn antennas to compensate for the additional free space path loss.

Fig. 1 shows the schematic of the system for the 300 GHz superheterodyne system using lower frequency mixers. To provide an I and Q signal two mixers need to be used for both transmitter and receiver, giving a total of four used mixers. According to their data sheets [5], the chosen mixers have an RF operation frequency between 7.5 GHz and 20 GHz with an IF frequency range up to 7.5 GHz. Although this range covers the frequency bands X, Ku and K they will be, for simplicity, referred to as X-band mixers. The LO is provided coherently at 10 GHz. To generate the complex IQ-data signals, an order 15 pseudo-random binary sequence (PRBS15) was generated in the AWG and then mapped to complex symbols depending on the chosen modulation format. On the receiver side, the signal is captured by a very fast oscilloscope and off-line digitally post-processed using an analyzer software. The software performs the carrier recovery and frequency equalization to compensate for the frequency and phase drift of the LO signals and for the frequency response of the overall transmission system.

IV. High Data Rate Transmission

To maximize the available RF bandwidth for the 300 GHz circuits, the LO frequency of the X-band mixers is set to 10 GHz. Given a maximal IF frequency of 7.5 GHz for the X-band mixers, the IF bandwidth of the overall superheterodyne system reaches around 8 GHz. Therefore, the expected symbol rate is around 6 GBd, considering a root raised cosine filter with a roll-off factor of 0.35. Fig. 2 shows the frequency spectrum for both the IF signal coming out of the X-band mixers, at an LO frequency of 10 GHz, and the RF signal. The LO input at 8.33 GHz gets multiplied by a total factor of 36, leading to an RF carrier frequency of 300 GHz. Since no filters are used, the RF signal contains both lower side band (LSB) and upper side band (USB). A distance of 12 GHz lies between the two bands for the maximal IF bandwidth of 8 GHz. The upper frequency of the LSB is at 294 GHz and the lower frequency of the USB is at 306 GHz. Thus, no

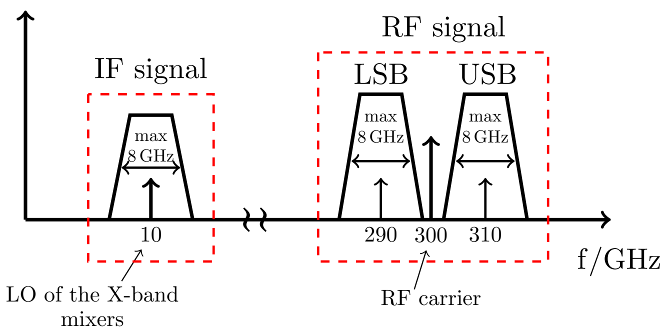

Fig. 2. Frequency spectrum of the IF and RF signals.

interference between the LSB and USB occurs. The mixer in the 300 GHz RX down-converts both bands in the same IF centered around 10 GHz.

A reference measurement of the equipment is carried out by connecting the signal generator directly to the oscilloscope. Another performed reference measurement is the back-to-back (b2b) measurement of the X-band mixers, realized by connecting the up-converters directly to the down-converters. In this case, the RF signal generated by the transmitter X-band mixer is fed to the RF input of the X-band down-converter. The first experiments over the air are realized using the 300 GHz modules and the AWG. An applied carrier offset to the generated PRBS data stream ensures the superheterodyne concept. Finally, the 300 GHz transmitter and receiver are combined with the commercially available mixers, resulting in the setup presented in Fig. 1. Data transmissions over 50 cm are carried out with different symbol rates and modulations formats.

Signals of different modulation formats and symbol rates are transmitted using this link. Fig. 3 shows the performance of the superheterodyne system for 16QAM modulated signals. The figure also shows the comparison with the reference measurement of the equipment, the back-to-back measurement of the baseband mixers and the superheterodyne system using the AWG with an carrier offset of 10 GHz. For the reference measurement the EVM value remains below 2 %. For the back-to-back measurement of the X-band mixers the maximum symbol rate achieved with 16QAM modulation is 9 GBd. This exceeds the 6 dB bandwidth of the system and translates into a maximum possible data rate of 36 Gbps.

The results of the 0.5 m transmission using the final superheterodyne system (circle symbols) show a similar curve as the mixers in back-to-back configuration (triangle symbols). A constant degradation of EVM of around 5 % can be observed between these two cases. Although the bandwidth of the 300 GHz superheterodyne system is the same as the bandwidth of the baseband mixers in back-to-back configuration, the IQ imbalances are higher and have an impact on the quality of the transmission. The constellation diagram of the 6 GBd signal transmitted using the line of sight 300 GHz link shows higher IQ amplitude and phase imbalances than the constellation diagram of a signal with the same symbol rate and modulation format transmitted over the X-band mixers in back-to-back configuration.

The maximum transmitted symbol rates with the 300 GHz system, as presented in Fig. 1 are 9 GBd with QPSK and 6 GBd with 16QAM modulation. Therefore, data rates reach 24 Gbps using a low-cost X-band frequency up- and down-converters.

The results of the superheterodyne concept, where the AWG generates the IF with a carrier of 10 GHz are plotted in Fig. 3 using square symbols. The highest data rate reaches 60 Gbps for a 16QAM modulated signal. To show the linearity of the 300 GHz system, signals with higher order modulation formats are transmitted over the air. Fig. 4 shows constellation diagrams of the highest achieved symbol rates for the modulation formats: 32QAM, which reaches 40 Gbps and 64QAM which reaches 12 Gbps. Especially in a superheterodyne multi-channel system a high linearity leads to a significant increase in data rate. The validation of the concept enables the use of a channel multiplexing at system input, to optimize the total data capacity by using an aggregation of low baud rate (few GBd) channels rather that a single carrier with huge payload. This approach, demonstrated here for X-band in I/Q signals is by essence compatible with existing modems operating up to 60 GHz, for up to THz bands up and down conversion.

To demonstrate the operation of the system over higher distances, a 10 m wireless link was established within the laboratory. This link was realized by first radiating the 300 GHz in the free space using conical horn antennas, fed by a WR3.4 (220-325 GHz) band. Such antennas provide a typical gain of about 25 dBi. Then the signal was collimated using a 100 mm teflon lens leading to a total estimated gain of around 38 dBi. The same configuration of lens/horn is used for signal detection at the receiver. Fig. 5 shows a view of the transmitter and receiver. The 10 m transmission is obtained with a reflection on a mirror placed at 5 m distance from the emission/detection modules. An attenuator is placed in front of

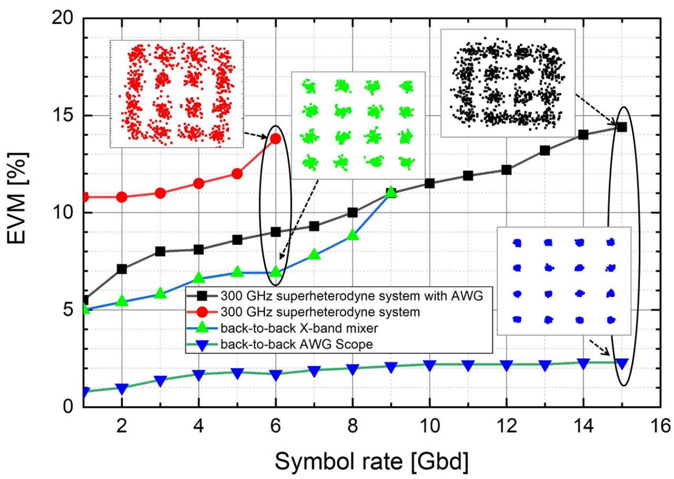

Fig. 3. Performance of the superheterodyne system versus symbol rate for 16QAM modulation format.

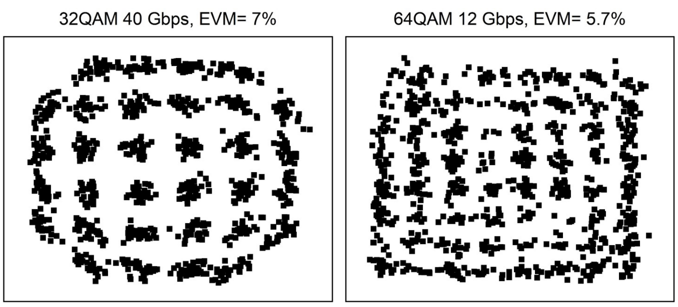

Fig. 4. Constellation diagrams of higher order modulation formats of the 300 GHz superheterodyne system using the AWG with an offset frequency of 10 GHz.

Table 1. State of the art wireless links at 300 GHz using only electronic devices with different technologies.

Ref	Technology	Frequency	Data rate	Distance	Architecture	Modulation Format
[6]	40 nm Si-CMOS	300 GHz	20 Gbps	10 cm	superheterodyne	16-QAM
[1]	80 nm InP-HEMT	272-302 GHz	100 Gbps	2.22 m	superheterodyne	16-QAM
[7]	130 -nm SiGe BiCMOS	220-260 GHz	100 Gbps	1 m	zero-IF	16-QAM
[8]	35 nm InGaAs mHEMT	224-256 GHz	96 Gbps	1 m	zero-IF	8-PSK
This work	35 nm InGaAs mHEMT	285-315 GHz	56 Gbps	10 m	superheterodyne	16-QAM

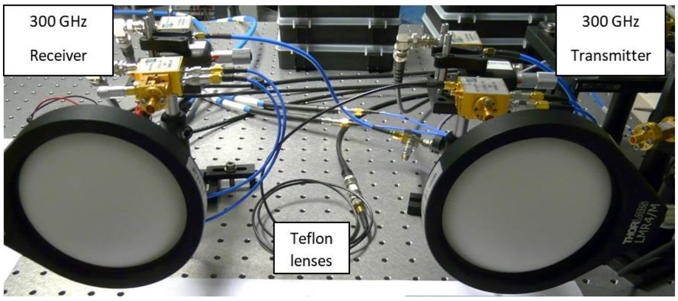

Fig. 5. Setup of the 10 m transmission using collimating dielectric lenses.

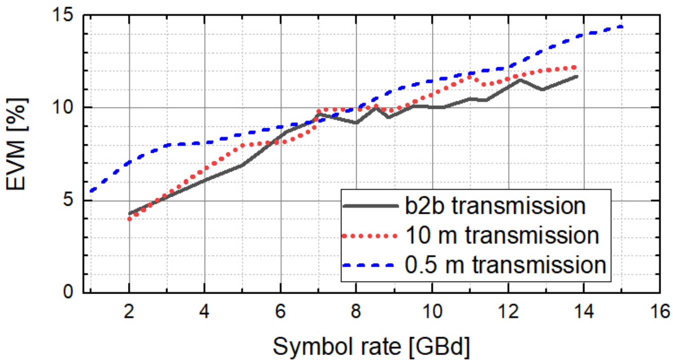

Fig. 6. Performance comparison of the 300 GHz superheterodyne link for 16QAM modulated signals with various symbol rates under different scenarios.

the receiver to achieve the optimal RF input power of around $-43\,\mathrm{dBm}$, since the transmitted output power, $-5\,\mathrm{dBm}$, the free space path loss, $100\,\mathrm{dB}$, and the total gain of the antennas, $72\,\mathrm{dBi}$, would lead to an RF input power of $-31\,\mathrm{dBm}$. The same attenuator is used in the back-to-back configuration, where the transmitted RF power is directly connected to the RF input of the receiver.

Data transmissions using the 300 GHz superheterodyne link with the AWG generating the IF with a carrier of $10\,\mathrm{GHz}$ over $10\,\mathrm{m}$ are conducted and compared to the low distance transmission, $0.5\,\mathrm{m}$ and with the back-to-back configuration. Fig. 6 shows the results of this comparison for 16QAM modulated signals of different symbol rates. The three transmissions show very similar performances, which validates the superheterodyne concept also for longer distances and makes it suitable for future indoor wireless applications.

V. State-of-the art Wireless Links at 300 GHz

The potential of terahertz communications is shown by the manifold of wireless links above 100 GHz developed in the past decades and their impressive reached data rates. Table 1 shows a summary of high-data-rate wireless links using electronic devices only. All these successful experiments demonstrate that the challenge of designing THz transmitters and receivers can be overcome and that the next big challenge is the development of baseband circuitry that can handle the high data rates.

VI. Conclusion

This paper reports on a 300 GHz superheterodyne system, that reaches a maximum data rate of $60\,\mathrm{Gbps}$ and can cover distances up to $10\,\mathrm{m}$. The link shows compatibility to low-cost existing baseband solutions and to the new THz frequency standard [3].

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