(Draft version)

Mobile Terahertz 6G Communications Enabled by Integrated Photonic-Assisted Beam Steering Antennas

J. Tebart[(1)], P. Lu[(1)], T. Haddad[(1)], S. Iwamatsu[(1)], J. Lackmann[(1)], J.L. Fernandez-Estevez[(1)] and A. Stöhr[(1)]

[(1)] Universität Duisburg-Essen, ZHO/ Optoelektronik, Duisburg, Germany, andreas.stoehr@uni-due.de

Abstract *We present photonic-assisted on-chip multi-beam THz leaky wave antennas for short-range Terahertz 6G. Experimentally, multi-beam mobile communications at 0.3 THz with an overall capacity of 48 Gbps, maximum net user data rate up to 20.4 Gbps and beam steering with a speed of ~18°/s is demonstrated.*

Introduction

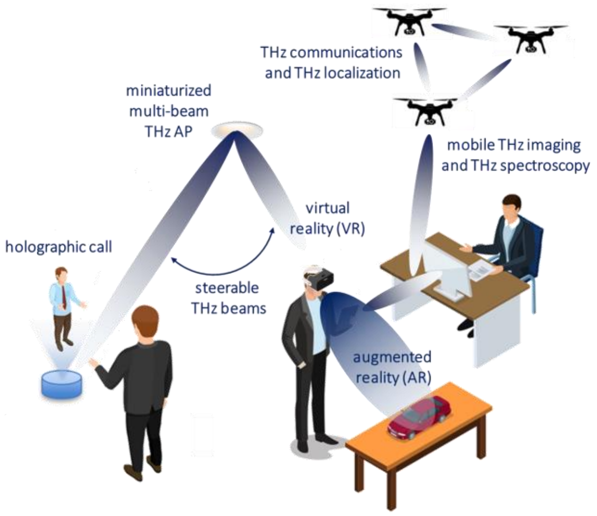

Fig. 1: Potential short-range 6G use cases [1].

Despite the progressing roll-out of 5G mobile networks, the desire for increasing data rates persists. Short-range applications such as virtual or augmented reality (VR/AR) with multiple users or kiosk downloads will require data bandwidths that easily outperform even latest 5G technology. In addition, new functionalities such as precise user equipment (UE) localization, mobile material characterization or imaging which are envisaged to become an integral part of future wireless systems and will require even substantially wider spectrum to be used [1].

In view of enabling such new applications and services, IEEE and ITU have recently ratified standards which opens up the use of a channel bandwidth up to 69 GHz in the range between 252.72-321.84 GHz for IEEE 802.15.3d [3] and 68 GHz between 275-450 GHz for ITU RE.2416 [4]. Several unique challenges, however, have still to be addressed to achieve the full potential of THz communications. For instance, THz transmission incurs a very high free-space path loss (FSPL), which requires the use of directive high gain antennas. Consequently, THz beam steering technology has become the focus of physical layer developments owing to its key importance for mobile THz communications, high-resolution imaging or mobile spectroscopy as illustrated in Fig. 1. Currently, several optical and electronic THz beam steering technologies are being investigated, ranging from more simple mechanical scanning over THz beam switching up full blown phased arrays [5]. Photonics-assisted THz beam steering may be favorable due to the inherent wide bandwidths that can be processed in the optical domain. However, despite the intensive R&D work, to our knowledge, there has not been a demonstration of a mobile THz 6G communication system yet. In this paper, we report on multi-beam THz communications using a photonic-assisted chip-integrated THz leaky wave antenna (LWA) array.

The fabricated LWA allows THz beam steering by optical means in the 0.3 THz band with a wide steering angle. Experimentally, a large overall data capacity for multiple users and a high individual user data rate are achieved using OFDM-QAM optical modulation. Furthermore, we investigate photonic-assisted THz beam steering achieved via optical laser frequency tuning and experimentally demonstrate a THz steering angle speed of 18°/s which supports high-capacity human-centered mobile UEs in indoor scenarios.

978-1-6654-3868-1/21/$31.00 ©2021 IEEE

InP-based chip-integrated 0.3 THz LWA

The on-chip THz LWA is based on a microstrip transmission line with altogether 32 rectangular stubs, placed on both sides of the microstrip to produce fast waves which can be radiated [6]. A substrate-transfer technology using a silicon wafer as a mechanical carrier substrate is established in order to be able to fabricate the LWA on a 50-µm thin InP substrate. The thin InP substrate is necessary to reduce the number of surface wave modes and achieve a high antenna gain [6]. For probing the antennas, the LWAs are integrated with on-chip grounded coplanar waveguide to microstrip-line (GCPW-MSL) THz transitions. Moreover, a hemicylindrical Teflon lens is designed to increase the antenna´s directivity. The simulated H-plane beam pattern of the LWA with the hemicylindrical lens is shown in Fig. 2. As can be seen, the antenna steers quasi-linearly towards endfire from 6° to 39° when changing the frequency between 0.28 THz and 0.33 THz. Here, 0° corresponds to the broadside direction. The linear steering behavior of ~0.7°/GHz was confirmed experimentally, showing a maximum angle variation below 4° for all frequencies. For all beam directions, the simulated directivity is approximately 23 dBi, as can be seen from Fig. 3. This figure is in good agreement to the measured values. Also, the simulated and the measured 3-dB beam width are in very good agreement, which can also be seen from Fig. 3.

Mobile THz communications

For studying short-range mobile THz communications, the LWA has been implemented into the THz communication set-up schematically shown in Fig. 4. The set-up consists of the THz transmitter which was built

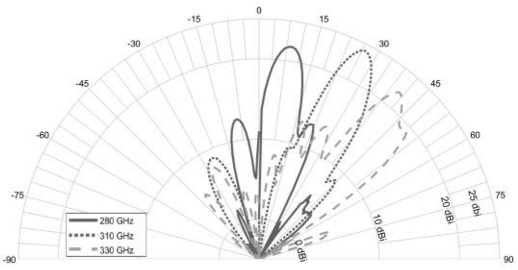

Fig. 2: Simulated far-field radiation pattern of the LWA for frequencies of 280 GHz, 310 GHz and 330 GHz including a hemicylindrical Teflon lens.

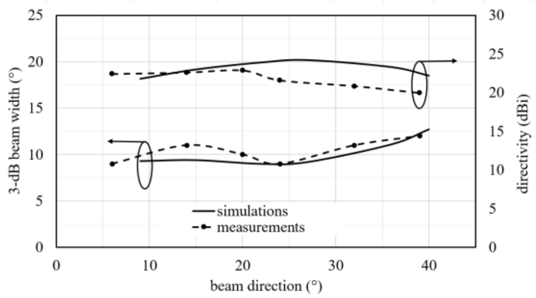

Fig. 3: Simulated and measured 3-dB beam width and directivity of the fabricated LWA including the hemicylindrical Teflon lens.

by connecting the LWA to a THz uni-travelling carrier photodiode with an output power of -14 dBm @ 0.3 THz. The THz waveform is generated using the THz transmitter by heterodyne mixing the modulated optical signal with an optical LO. Both optical signals are generated by free-running integrable tunable laser assemblies (ITLA) which feature an external cavity laser diode with a low linewidth of ~25 kHz. The baseband OFDM data signal with an IF-carrier is generated using an arbitrary waveform generator (AWG) with an analog bandwidth of 20 GHz and it is modulated onto the optical signal using a Mach-Zehnder modulator. Thereby, the THz waveform represents an IF-OFDM signal which allows the utilization of an envelope detector on the receiver side [7]. After wireless transmission, the signal is received with a horn antenna (24 dBi gain) and amplified by ~28 dB with a low noise amplifier before envelope detection is performed using a Schottky-barrier diode (SBD). Subsequent data analysis is then carried out in digital domain. To enable mobility, the THz receiver is mounted onto a goniometer. This way, the receiver can be placed at all positions within the steering range of the LWA.

The experimentally measured bit error rates (BER) for a single user using IF-OFDM-4QAM modulation and a 12 GHz bandwidth are shown in Fig. 5. For the whole scanning range of the LWA, the measured BER is below

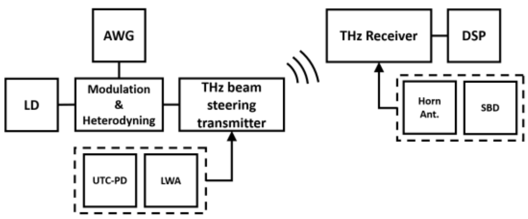

Fig. 4: Concept of the transmission system. The transmitter side features optical heterodyning for THz beam steering via a LWA. At the receiver side, an SBD envelope detector is utilized for down-conversion of the THz signal to IF

the HD-FEC limit (3.8·10^{-3}) [8]. Thus, a net data rate of ~20.5 Gbps per beam is achieved at all steering angles considering the 7% HD-FEC overhead and additional pilot tones.
The fact that the BER performance is almost stable with respect to the steering angle can also be seen from the estimated link budget which is depicted in Tab. 1. As can be seen, the RF input power to the SBD is about -10 dBm for all angles.
Furthermore, multi-beam operation has been investigated experimentally, revealing that the antenna can support up to 12 users with a data rate of 4 Gbps each. The overall antenna capacity is thus 48 Gbps.

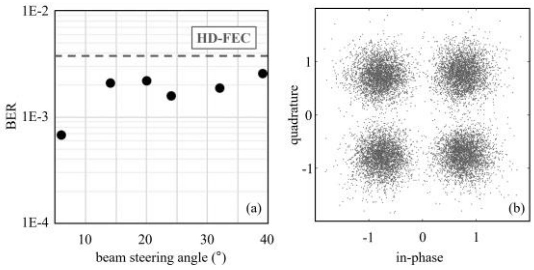

Fig. 5: Bit error rates at different steering angles for a wireless distance of 6 cm and IF-OFDM-4QAM modulation and 12 GHz bandwidth showing below 7% HD-FEC performance (a). Corresponding constellation diagram at a steering angle of 24° (b).

Tab. 1: Link budget for beam directions of 6°, 20° and 32° at a wireless distance of 6 cm.

beam direction (°)	6	20	32
PD output power (dBm)	-14.27	-13.64	-14.46
probe loss (dB)	4.73	5.11	5.79
LWA gain (dBi)	14.08	14.01	14.76
FSPL (dB)	56.95	57.55	58.11
horn antenna gain (dBi)	23.63	24.03	24.56
THz LNA gain (dB)	27.95	28.82	29.92
SBD input power (dBm)	-10.29	-9.46	-9.12

THz Beam Steering Speed

To study at which speed the THz beam can be steered, the ITLA laser frequency was swept over a 50 GHz bandwidth at different nominal tuning speeds between 10 GHz/s and 60 GHz/s. Each time the beam steering antenna points towards the THz receiver, a voltage pulse is generated by the SBD, as can be seen in Fig. 6 for a nominal tuning speed of 30 GHz/s. Experimentally, an asymmetric tuning behavior with a slower up- chirp speed is observed, as it is depicted in Fig. 7. Also, a saturation can be observed which limits the maximum steering speed. This effect can be traced back to the tuning properties of the laser since they are based on changing the laser's current as well as temperature. This results in a maximum steering speed of about 17.7°/s which is only limited by the tuning speed of the ITLA. Much higher steering speeds can be expected for fast frequency tunable lasers.

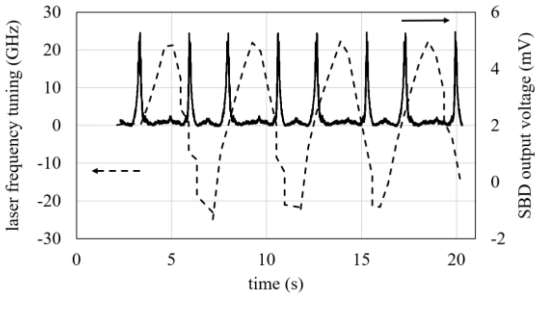

Fig. 6: Laser frequency tuning according to the ITLA control software with a tuning speed of 30 GHz/s (dashed line). A pulse is generated each time the antenna points towards the SBD receiver (solid line).

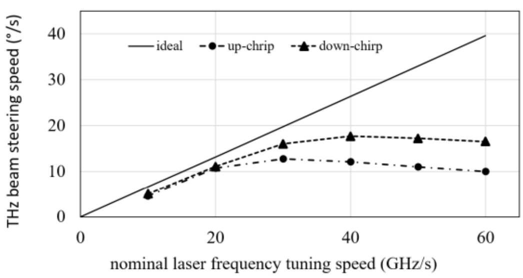

Fig. 7: THz beam steering speed versus the nominal laser frequency tuning speed according to the ITLA setting.

Conclusions

Mobile THz 6G communications using a chip-integrated photonic-assisted leaky wave antenna is experimentally demonstrated. With a steering speed of up to ~18°/s, a maximum net single user data rate of ~20.5 Gbps and an overall capacity of ~48 Gbps, short-range 6G use cases such as VR/AR or download kiosks can be supported.

References

[1] C. Han, Y. Wu, Z. Chen, and X. Wang, "Terahertz Communications (TeraCom): Challenges and Impact on 6G Wireless Systems", arXiv, 2019.

[2] C. de Lima et al., “6G White Paper on Localization and Sensing”, white paper, (6G Research Visions; No. 12), http://urn.fi/urn:isbn:9789526226743.

[3] V. Petrov, T. Kürner and I. Hosako, “IEEE 802.15.3d: First Standardization Efforts for Sub-Terahertz Band Communications toward 6G”, IEEE Communications Magazine, pp. 28-33, November 2020.

[4] International Telecommunication Union, “Technical and operational characteristics and applications of the point-to-point fixed service applications operating in the frequency band 275-450 GHz,” https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-F.2416-2018-PDF-E.pdf.

[5] X. Fu, F. Yang, C. Liu, X. Wu, and T. Jun Cui, „Terahertz beam steering technologies: From phased arrays to field programmable metasurfaces“, Adavnced Optical Materials, vol. 8, 2020.

[6] P. Lu, T. Haddad, B. Sievert, B. Khani, S. Makhlouf, S. Dülme, J. F. Estévez, A. Rennings, D. Erni, U. Pfeiffer, and A. Stöhr, “InP-based THz beam steering leaky-wave antenna,” IEEE Trans. Terahertz Sci. Technol. 11(2), pp. 218–230, 2021.

[7] M. F. Hermelo, P.-T. Shih, M. Steeg, A. Ng’oma, and A. Stöhr, “Spectral efficient 64-QAM-OFDM terahertz communication link,” Opt. Express 25(16), pp. 19360–19370, 2017.

[8] Z. Li, M. S. Erkılınç, S. Pachnicke, H. Griesser, B. C. Thomsen, P. Bayvel, and R. I. Killey, “Direct-detection 16-QAM Nyquist-shaped subcarrier modulation with SSBI mitigation,” in Proceedings of IEEE, International Conference on Communications (ICC), pp. 5204–5209, 2015.

DOI: 10.1109/ECOC52684.2021.9605939
URN: urn:nbn:de:hbz:465-20230330-115024-2