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Mobile THz communications using photonic assisted beam steering leaky-wave antennas

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Abstract: THz communications is envisaged for wide bandwidth mobile communications eventually reaching data capacities exceeding 100 Gbit/s. The technology enabling compact chip-integrated transceivers with highly directive, steerable antennas is the key challenge at THz frequencies to overcome the very high free-space path losses and to support user mobility. In this article, we report on mobile and multi-user THz communications using a photonic THz transmitter chip featuring 1D beam steering for the first time. In the proposed approach, 1D THz beam steering is achieved by using a photodiode excited leaky-wave antenna (LWA) in the transmitter chip. The on-chip LWA allows to steer the directive THz beam from 6° to 39° within the upper WR3-band (0.28-0.33 THz). The antenna's directivity is 14 dBi which is further increased to 23 dBi using an additional hemicylindrical Teflon lens. The 3-dB beam width and coherence bandwidth of the fabricated THz transmitter chips with lens are 9° and 12 GHz, respectively. The proposed approach allows steering the THz beam via the beat frequency of an optical heterodyne system at a speed up to 28°/s. Without using a THz amplifier in the transmitter chip, a data rate of 24 Gbit/s is achieved for a single user for all beam directions and at short wireless distances up to 6 cm. The wireless distance is successfully increased to 32 cm for a lower data rate of 4 Gbit/s, still without using a transmitter amplifier. Also, multi-user THz communications and the overall capacity of the developed THz transmitter chip is studied revealing that up to 12 users could be supported together with a total wireless data capacity of 48 Gbit/s. Fully integrated 2D transmitter chips are expected to reach wireless distances of several meters without additional amplifiers.

1. Introduction

In the last few years, the demand of high-capacity mobile communications has been growing explosively. Upcoming applications such as augmented reality (AR), virtual reality (VR), cloud computing, 8K video broadcast, connected machines and in general real-time applications require much higher data capacities than current mobile generations can support. These can be achieved by using wider transmission bandwidths and higher spectral efficiencies [1–3]. At frequencies of up to 100 GHz, the contiguous bandwidth is limited by 14 GHz [4] and consequently, THz waves (>100 GHz) have drawn more and more attention for mobile communications due to the available broad bandwidth. For the 275-450 GHz band, a bandwidth of 68 GHz is allocated for communication purposes by the International Telecommunication Union [5]. At higher frequency beyond 1 THz, even several hundreds of GHz bandwidths are expected to be regulated. Other advantages of THz communications include the fact the much shorter wavelength allows the development of chip-integrated THz front ends. Furthermore, mobile THz communications are more difficult to be eavesdropped due to the highly directional beams and the limited propagation distance compared to legacy mobile communications using sectorial antennas [6,7].

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Recently, THz communication systems featuring photonic components as transmitters [8–12] have been intensively investigated taking advantage of the developments of mature lasers, modulators, fiber amplifiers and photodiodes (PD). In contrast to electronic THz transmitters, photonic front ends benefit from the broadband performances of modern PDs used to generate the THz carriers and also from the low-loss optical fibers enabling centralized radio access networks. Most recent research works on THz communication systems focused on point-to-point transmission links and the development of ultra-high gain antennas for long-range wireless communications [9–12]. But besides backhaul links, most of the promising applications such as real-time IoT or AR/VR require mobility and multi-user support. This leads to the technological challenge of developing integrated THz transmitter and receiver chips that support THz beam steering to overcome the free-space path loss (FSPL) in the THz domain and to enable user mobility and multi-user operation. Very recently, first concepts enabling THz beam steering based on photonic phased arrays have been demonstrated by using fiber-optic delay lines [13], free-space optical phase shifter [14] or thermo-optic phase shifter [15] for the optical beam control circuitries. However, complex optical phase shifters or true time delay feeders still prevent from monolithic integration. In comparison with optical phased arrays, PD exited leaky-wave antennas (LWA) provide a less complex beam control. For LWAs, the beam direction can be simply tuned by changing the operating frequency which can be easily achieved in photonics over huge bandwidths by tuning the beat frequency of an optical heterodyne system. In the microwave region, several photonic assisted wireless communication systems using LWAs have been demonstrated. In [16], a PD integrated LWA using printed circuit board technology for E-band was developed. Using on-off keying modulation, an error-free transmission of 2.15 Gbit/s for a link distance of 25 cm was achieved using two lenses. A steerable 60 GHz band PD excited LWA with a maximum user data rate up to 6 Gbit/s was demonstrated in [17] using 64 quadrature amplitude modulation (QAM) orthogonal frequency-division multiplexing (OFDM) modulation. In addition, the inherent frequency correlative beam steering of LWAs makes them attractive not only for tracking of a single mobile user [18], but also for multi-user scenarios. In [19], a single-feed LWA was reported for simultaneous transmission to up to three users for V-band frequencies.

However, to the best of our knowledge, no THz communication systems using beam steering antennas have yet been shown. In this work, we first report on a photonic assisted beam steering THz communication system based upon a planar on-chip THz LWA. In the next section, the beam steering capabilities of the fabricated THz transmitter and the generated THz beam patterns are experimentally determined and compared to simulation results. Next, the fabricated THz transmitter chip is employed for single user mobile THz communications. Finally, guard bands required for multi-user operations are experimentally determined to study the maximum user number and total data capacity that can be supported.

2. 1D beam steering THz LWA transmitter chip

The planar THz LWA used in this work is intentionally fabricated on an InP substrate for future monolithic integration with InP-based photodiodes [20,21]. The fabricated LWAs utilize 32 periodic rectangular stubs on both sides of the microstrip (see inset in Fig. 1). An on-chip grounded coplanar waveguide to microstrip-line (GCPW-MSL) THz transition is integrated to allow experimental analysis of the fabricated antenna chips using ground-signal-ground (GSG)-probes. The overall length of the 0.3 THz LWA including the transition is 6.6 mm. To suppress the number of surface wave modes and increase the radiation efficiency, the LWA is fabricated on a 50-μm thin InP substrate ($\varepsilon_r \approx 12.4$, $\tan\delta \approx 0.003$) using a silicon substrate-transfer technology [20]. Using CST Studio Suite, an additional hemicylindrical lens is developed to further increase the directivity of the on-chip LWA. The hemicylindrical lens with a diameter of 3.8 mm is fabricated using Teflon with a permittivity of $\varepsilon_r \approx 2.1$. Figure 1(a) shows the simulated

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H-plane far-field radiation patterns of the LWA with the lens placed 2.7 mm above the antenna. As can be seen, the beam direction changes from broadside (0°) towards endfire (90°) when increasing the frequency from 0.28 to 0.33 THz. The side mode suppression is in excess of 10 dB. For experimental characterizations, a THz on-wafer antenna measurement system [22] is used to determine performances of the LWA including the lens. It should be noted that the LWA also allows to steer the THz beam towards backfire, i.e., beam directions <0°. However, this could not be experimentally determined as in this case the transmitted THz beam is partly reflected by the GSG-probe. Figures 1(b)–1(d) show the simulated and measured beam direction, 3-dB H-plane beam width and the antenna's directivity. Also, the simulated LWA performances without the lens are included in these figures for comparison.

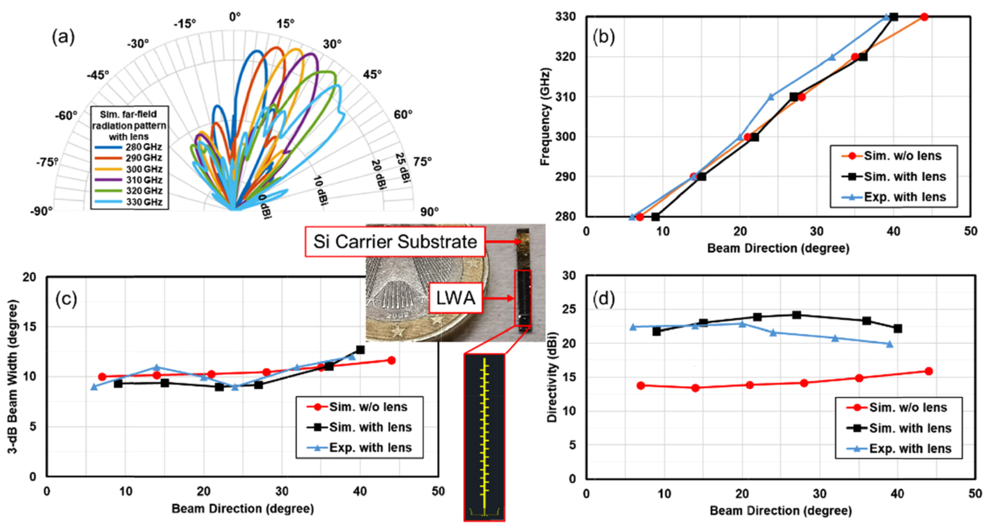

Fig. 1. Simulated H-plane far-field radiation patterns of the planar InP-based on-chip LWA with the hemicylindrical Teflon lens (a). Simulated and experimentally characterized beam direction (b), 3-dB H-plane beam width (c) and directivity (d) of the LWA without and with the hemicylindrical Teflon lens. The inset shows a photo of the fabricated LWA and a schematic view.

As can be seen from Fig. 1(b), the THz beam scans from 6° to 39° in a quasi-linear manner with ~ 0.7°/GHz when the carrier frequency is tuned between 0.28 and 0.33 THz. Thus, the overall scanning range is 33°. It can also be observed that the beam direction is only barely affected by the hemicylindrical lens. Here, a maximum deviation of only 4° is observed at 330 GHz which is traced back to the lens. Figure 1(c) shows that the average 3-dB H-plane beam width of the on-chip antenna without the lens is ~ 11° for the whole steering range. The use of the lens leads to a slightly reduced beam width for beam directions closer to broadside. For endfire, the lens widens the beam width slightly up to 13°. Overall, a good agreement between the measured and the simulated 3-dB beam widths is found and the beam width is rather unaffected by the lens, as it was expected. The maximum deviation is only ±1° for the whole steering range. From the measured minimum 3-dB beam width of 9° and the beam steering rate of 0.7°/GHz, the coherence bandwidth of the antenna is determined to be in excess of 12 GHz for the whole scanning range. The simulated directivity of the on-chip LWA can be seen from Fig. 1(d), showing an antenna directivity of ~ 14 dBi for the full scanning range. Using the hemicylindrical Teflon lens substantially increases the directivity up to ~ 23 dBi. This is further verified by experimental measurements which agree to the simulated results for beam directions of up to 20°. Only above 20°, we observe a slightly lower directivity than expected with a maximum deviation of ~ 2 dB. This is traced back to the non-perfect shape of the manufactured Teflon lens and the misalignment during measurements.

3. Single-user mobile THz communications

3.1. System set-up

A schematic overview of the system set-up for THz communications is shown in Fig. 2. An intermediate frequency (IF) OFDM waveform is generated in the digital domain and converted to the analog domain using an arbitrary waveform generator (AWG) (*Keysight M9505A*) with an analog bandwidth of 20 GHz. Employing IF modulation is motivated by the envelope detection approach since it enables phase recovery at the wireless receiver for complex modulation schemes such as QAM [8]. After subsequent IF amplification using a medium power amplifier (MPA) with ~30 dB gain, the waveform is modulated onto a 1.55-μm optical carrier (laser 1) by means of a Mach-Zehnder modulator (MZM) with 40 GHz bandwidth. Here, the optical carrier is provided by a free running integrable tunable laser assembly (ITLA) which comprises an external cavity laser diode and additional control circuits. The external cavity laser allows to tune the optical wavelength and still provides a reasonably low optical linewidth of ~ 25 kHz. After optical amplification, the signal is transmitted to the wireless front end via standard single mode fiber (SMF). Then, to transfer the OFDM waveform to the THz region, a second ITLA (laser 2) with a beat frequency in the THz range w.r.t. laser 1 is employed for optical heterodyning in a uni-travelling-carrier photodiode (UTC-PD) with a high output power of ~ -14 dBm at 0.3 THz. Laser 3 allows to generate a second THz carrier and is only used for the experimental characterization of multi-user scenarios (see section 4). The optically generated THz OFDM waveform is then radiated into free space using the fabricated InP LWA connected to the UTC-PD via a GSG-probe (*FormFactor I325-T-GSG-100BT*). To increase the antenna's directivity, the hemicylindrical Teflon lens is placed above the LWA as discussed above. After wireless transmission, the THz waveform is received by a standard WR2.8 diagonal horn antenna with 24 dBi gain and is further amplified via a THz low noise amplifier (*Radiometer Physics LNA 250-350 25 8*) with ~ 27.5 dB gain. Down-conversion to IF is then carried out using a zero-biased Schottky-barrier diode (SBD), *(Virginia Diodes WR2.8 ZBD-F40*) with a maximum available response rate of ~ 40 GHz. Frequency drifts between the data carrier and the LO can

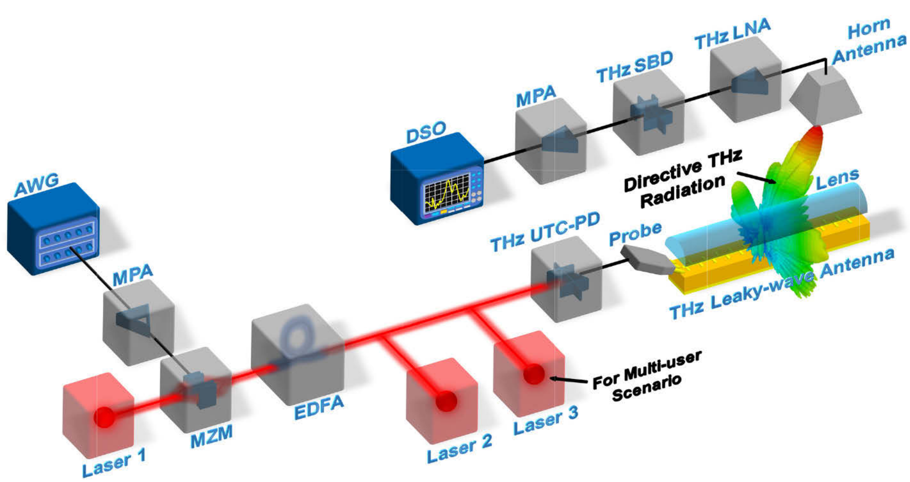

Fig. 2. Schematic architecture of the THz communication system set-up using the photonic LWA with the hemicylindrical Teflon lens.

be neglected for this receiver setup in comparison with a heterodyne detection approach, thus avoiding the need for locking the lasers [8,23]. For demodulating the IF-OFDM signal in the digital domain, the waveform is digitized by a high frequency digital sampling oscilloscope (DSO), (*Keysight DSA-Z 634A*) and then analyzed using off-line digital signal processing. The highest data bandwidth of this THz communication system is expected to be ~ 12 GHz which is limited only by the coherence bandwidth of the LWA.

Figure 3 shows photographs of the THz communication system set-up with the Teflon lens placed ~ 2.7 mm above the LWA. The wireless receiver is installed on a goniometer to support angular dependent measurements and for emulating a mobile user.

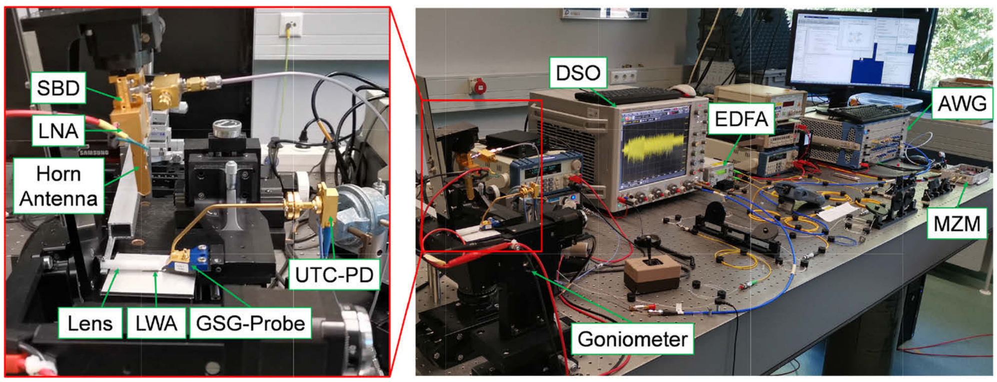

Fig. 3. Photographs of the THz communication system using the photonic LWA with the hemicylindrical Teflon lens.

For a wireless distance of 6 cm, the link budget of the system is estimated in Table 1 for beam directions of 6°, 20° and 32°. As intended, the system performance is almost independent on the wireless carrier frequencies. Also, the FSPL is almost the same for all carrier frequencies, i.e., all beam directions. The input power to the SBD is around -9.6 dBm for all beam directions.

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

Beam Direction (degree)	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

3.2. Experimental results

First, the nonlinearity of the whole receiver setup including LNA, SBD and MPA is characterized. This is carried out by measuring the SNR as a function of the UTC-PD output power for a 4-QAM IF-OFDM data signal with a bandwidth (BW) of 4 GHz and an IF of 4 GHz. For this experiment, the beam direction is set to 6° and the wireless distance between the tip of the horn antenna and the LWA is 6 cm. The bias of MZM is set be ~ 2 V to minimize signal-signal beating interference (SSBI) [23]. The number of subcarriers is 512, whereas 16 subcarriers are used as pilots to compensate carrier-frequency offset. As can be seen in Fig. 4, the measured SNR increases from ~ 6.8 dB to ~ 16.1 dB quasi-linearly with the PD output power. There is a good agreement with the expected square-law response of an SBD [24] which indicates that the wireless receiver is not saturated.

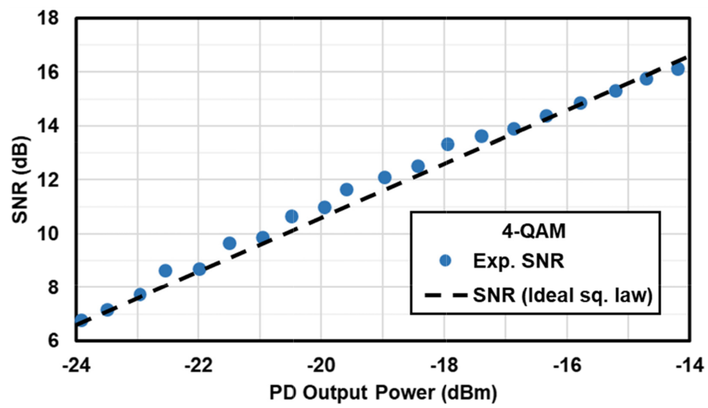

Fig. 4. Measured SNR of a 4-QAM IF-OFDM data signal with a bandwidth of 4 GHz at an IF of 4 GHz as a function of PD output power for a wireless transmission distance of 6 cm and a beam direction of 6°. The black dash line shows the SNR of an SBD as a function of PD output power assuming ideal square-law response without saturation effect after [24].

To investigate the beam steering capabilities of the THz communication system, we measured the BER as a function of the beam angles from 6° to 39°. Here, a stable BER has been found (see Fig. 5) which can be explained by the fact that the input power to the SBD receiver is nearly independent of the beam direction as detailed in Table 1. Here, 4-QAM IF-OFDM modulation and BWs of 8 GHz and 12 GHz at an IF of 6 GHz are used. For 8 GHz BW, a minimum BER of $8{\times}10^{-5}$ is observed at angles of 24° and 32°. At 39°, the maximum BER is $7.6{\times}10^{-4}$. For 12 GHz BW, the measurement shows a similar trend with a larger BER as expected. Overall, for both bandwidths, the BER are always below $3.8{\times}10^{-3}$ which is the limit for 7% over-head hard decision forward error correction (HD-FEC) [25]. Therefore, it can be concluded that a minimum net data rate of 20.46 Gbit/s is achieved for all beam directions using a 12 GHz BW. In the proposed system approach, the beam direction is controlled via the wavelength tuning of the LO laser. The laser allows a wavelength sweep speed of up to 40 GHz/s [26] which in turn means that the THz beam can be steered with an angular speed of 28°/s given the quasi-linear steering capability with 0.7°/GHz of the fabricated LWA.

In addition, the system performances are studied for larger wireless distances up to 34 cm using again 4-QAM IF-OFDM waveforms at a beam direction of 6°. The IF is fixed to 3 GHz for BWs of 2 GHz, 4 GHz and 6 GHz. As shown in Fig. 6, the BER increases for larger wireless distance due to the higher FSPL. For a BW of 6 GHz (data rate of ~ 12 Gbit/s), a wireless transmission distance for below HD-FEC level BER is achieved up to 16 cm. When reducing the BW to 4 GHz, the wireless link can be extended up to 20 cm, while for a data rate of 4 Gbit/s a wireless distance of 32 cm is achieved. To further increase the wireless distance in the meter range, one option would be a monolithic integrated 2D LWA array with an array of THz PDs which will not only avoid the ~ 5 dB loss of the GSG-probe, but also benefit from the array factor. This is further discussed in section 5.

The received 4-QAM constellations at a beam direction of 6° with a BW of 12 GHz at 6 cm and a BW of 2 GHz at 32 cm are shown in Fig. 7(a) and Fig. 7(b), respectively. As can be seen, the constellations are successfully recovered without wrapping.

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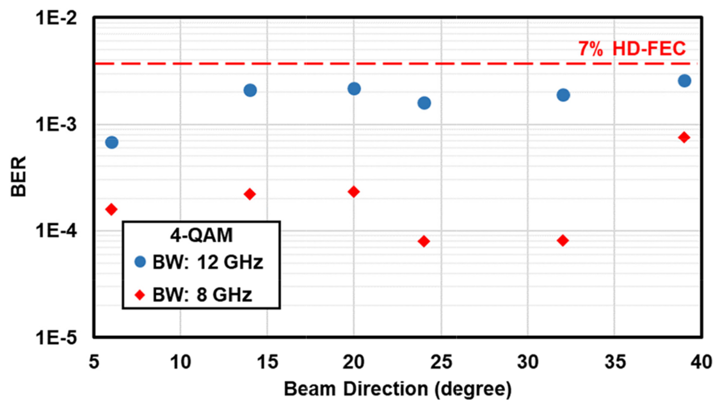

Fig. 5. Measured BER of 4-QAM IF-OFDM data signals with bandwidths of 8 GHz and 12 GHz from 6° to 39°. The IF frequency is 6 GHz.

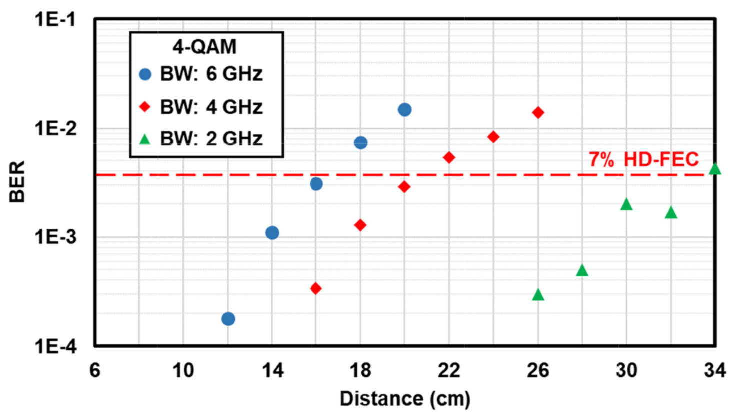

Fig. 6. Measured BER of 4-QAM IF-OFDM data signals for wireless transmission distances from 6 cm to 34 cm. The IF frequency is 3 GHz, and the beam direction is 6°.

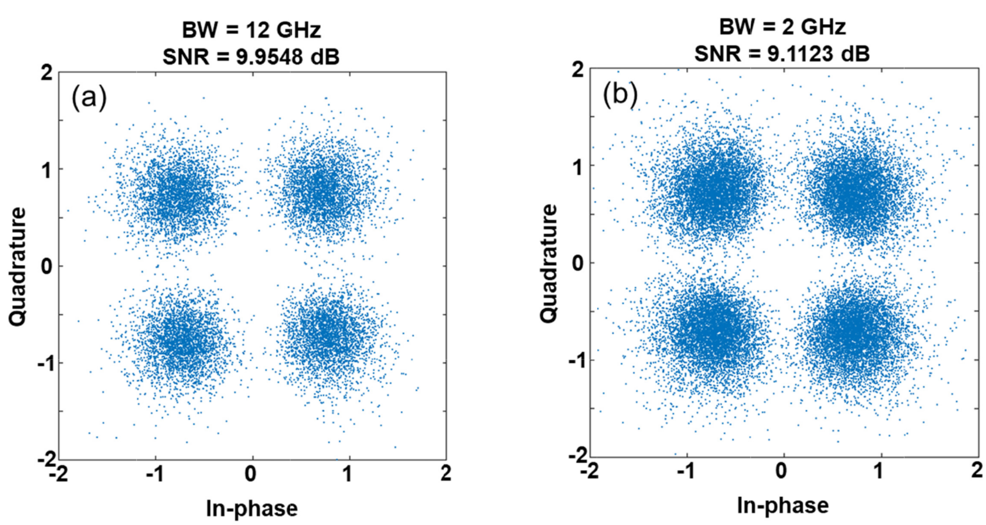

Fig. 7. Constellation diagrams of the received 4-QAM IF-OFDM signal with a bandwidth of 12 GHz at 6 cm (a) and a bandwidth of 2 GHz at 32 cm (b) after digital demodulation.

4. Multi-user THz communications

For conventional WiFi networks, omnidirectional antennas are commonly used to cover multiple users at different angular locations w.r.t. the router. For THz communications, such omnidirectional antennas are not quite feasible due to the much higher FSPL. A solution to this problem is to use antennas providing multiple directional beams at different directions simultaneously. In that context, the proposed approach using LWAs is attractive, as it allows to generate multiple beams at different directions simply by using a different carrier frequency for each user waveform. Since the performance of the developed wireless receiver is rather independent of the carrier frequency thanks to the envelope detection approach, multiple users (wireless receivers) can be supported by only one LWA. In the proposed photonic assisted system, which is based on optical heterodyning, multiple carriers can be generated by using optical LO lasers or by using an optical comb laser.

To survey the number of users and the total data capacity that the system can support, it is necessary to investigate the interference between two neighbored beams. For this study, an additional LO laser (laser 3) is added to the system set-up (see Fig. 2) in order to simultaneously generate and radiate two THz waveforms at different beam directions. To experimentally determine the minimum beam angle difference between two users, one beam is fixed at a direction of 6° while the second beam is moved closer to the first one until the BER for both users reaches the HD-FEC level of 3.8×10^{-3} due to interference between the two OFDM waveforms. This experiment is systematically carried out for different user bandwidths.

Experimentally, it is found that independent on the BW for each user, the guard band between two waveforms must be larger than 1 GHz for below HD-FEC transmission. The measured BER for different scenarios are summarized in Table 2.

Table 2. Measurement parameters and results for multi-user scenarios.

QAM	IF (GHz)	Data Bandwidth (GHz)	Data Rate (Gbit/s)	BER	Guard Band (GHz)	User Separation (degree)	User Number	Total Data Capacity (Gbit/s)
16	1	1	4	3.2×10^{-3}	1	3	12	48
16	3	2	8	7.8×10^{-4}	1	6	6	48
4	4	6	12	1.3×10^{-3}	1	10	4	48

Obviously, the number of users that could be potentially supported by the proposed approach is linked to the BW provided per user. For a wireless data rate of 12 Gbit/s for each single user, the minimum angular user separation must be 10° which results in up to 4 users that could be covered simultaneously by the fabricated LWA within the scanning range, i.e., 33°. This would lead to a total data capacity of 48 Gbit/s provided the spectral power density of the radiated three beams fulfills the requirements for below HD-FEC transmission. By reducing the BW, the SNR is increased which allows to use higher order QAM modulation such as 16 QAM. This way, a data rate of 4 Gbit/s is achieved even at a narrow bandwidth of only 1 GHz. In that case, users can be located much closer to each other. The total user number would increase up to 12, while the total data capacity remains 48 Gbit/s. Note that for a monolithic integrated PD/LWA, one could also exploit the beam directions towards backfire which are currently not usable due to reflections at the GSG-probe. This would theoretically double the number of users, and the overall capacity per antenna sector would increase up to 96 Gbit/s provided sufficient output power is available.

5. Conclusion

This article reports on a novel photonic assisted THz communication system supporting mobile and multi-user applications. By using a photodiode excited planar InP-based on-chip leaky-wave antenna, the direction of THz beams can be tuned via the beat frequency of an optical heterodyne

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system between 0.28 and 0.33 THz. To the best of our knowledge, this is the first experimental demonstration of THz communications with beam steering antennas.

For single user operation, a data rate of 24 Gbit/s is achieved within the antenna's scanning range of 33°. The scanning speed of 28°/s allows to steer the THz beam over the full scanning range within less than 1.2 seconds. Also, multi-user operation is investigated, revealing a minimum guard band of 1 GHz which in turn indicates that the proposed approach could support up to 12 users within the antennas coverage sector and a total capacity of 48 Gbit/s.

The wireless distance for below HD-FEC mobile single-user THz communications is currently limited to short-ranges. In the experiment, the PD output power at 0.3 THz is around -14 dBm resulting in a wireless distance of 32 cm for 4 Gbit/s. Both devices, the PD and the LWA used in this experimental study are intentionally fabricated on InP-substrate to allow future monolithic integration which is expected to increase the single user link SNR by about 5 dB (insertion loss of the GSG-probe). Depending on gain and noise factor, an additional amplifier will also help to increase the wireless distance because the link SNR is typically determined by the thermal noise of the THz receiver. In addition, a great progress w.r.t. a higher SNR can be expected from monolithically integrated LWA array configurations. A 10x PD/LWA array is expected to provide 10 dB higher RF output power due to free-space power combining. As discussed in our previous work [20], a directivity enhancement of ~ 9 dB is expected for such an array configuration in contrast to a single LWA. Since the hemicylindrical lens cannot be used for the 2D array, a reduction in the antenna's directivity of ~ 7 dB must be considered. In total, a monolithically integrated 10x PD/LWA array is expected to increase the link SNR by at least 16 dB compared to the single LWA as presented in this work, even without the use of an additional amplifier and the hemicylindrical Teflon lens. This way, the wireless distance should be extended well into the meter range making the proposed THz approach available for mobile IoT applications such as mobile users wearing AR/VR googles in an in-door environment.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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