# Recent Developments of Photonic Integrated Chips for THz Beamsteering

(invited paper)

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**Abstract** *This paper explores the use of PICs for THz beamsteering to overcome the high atmospheric attenuation and enable future THz 6G mobile communications. For the first time, photonic-assisted 2D THz beamsteering for THz 6G mobile communications is reported.*

## Introduction

The terahertz (THz) frequency range spans a wide range of the electromagnetic spectrum, from microwave to far infrared (0.1 - 10 THz). Besides other applications, the frequency range has tremendous potential for THz communications, particularly in the upcoming 6G era, which aims to achieve wireless data rates of up to 1 Tbps [1]. Recently, the first THz spectra between 252 - 450 GHz were identified, and regulatory bodies in IEEE and ITU-R have already issued new standards (IEEE 802.15.3d and ITU-R F.2416-0, respectively) for THz fixed wireless access (FWA) scenarios of up to 100 Gbps data rates [2, 3]. Nevertheless, a number of challenges and market barriers need to be overcome. On the physical layer, enabling THz beamsteering using chips to overcome the high free-space path loss (FSPL) at THz frequency [4], limiting the wireless propagation range, is of the highest priority. For FWA scenarios, highly directional antennas and lenses can effectively compensate for the FPSL, as reported in [5-7]. However, when it comes to mobile communication, beamsteering is crucial besides other challenges, including localizing user equipment (UE) during link setup, mobile user tracking, and beam handover in high-density UE scenarios.

This work reviews recent achievements in RF and photonic technologies for beamsteering. We mainly focus on photonic integrated circuits (PICs). For the first time to the best of our knowledge, a photonic-assisted chip for 2D beamsteering utilized in a mobile THz communication system is reported.

## Technologies of Terahertz Beamsteering

In recent years, there has been a rise in THz beamsteering technologies. For one-dimensional beamsteering, besides scaling up some conventional RF phased array solutions to the THz domain, linear CMOS-driven antenna arrays at a scale of 130 nm and even 40 nm [8, 9],

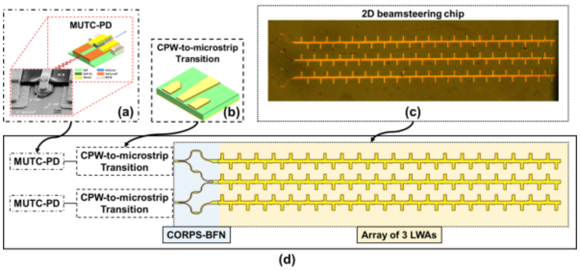


**Fig. 1:** (a) WR3.4-band THz MUTC photodiode and microscope image of the MUTC-PD in the inset [27], (b) concept of CPW-to-microstrip transition (c) fabricated THz 2D beamsteering chip [19], (d) concept of monolithically integrating the THz 2D beamsteering chip with MUTC-PDs.

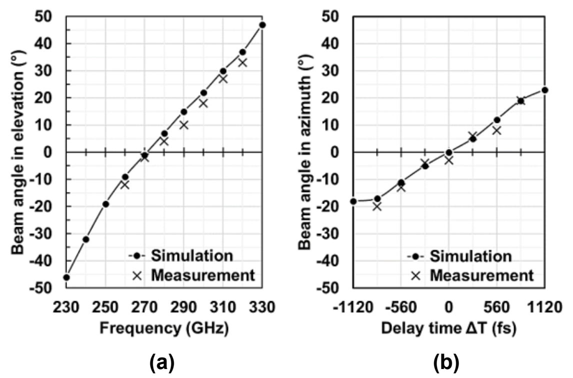


**Fig. 2:** (a) Changing the beam angle in elevation direction as a function of the frequency at $\phi$=0°, (b) the beam angle in azimuth direction as a function of the delay time $\Delta T$ at $f$ = 300 GHz ($\theta$ = 20°) [19].

photonic and photonic-assisted THz beamsteering technologies [10, 11], micro-electro-mechanical systems (MEMS) [12], and graphene arrays [13] have been reported.

For 2D THz beamsteering, only a few works have been reported yet. Examples include a variable structure utilizing a Luneburg lens or Metasurfaces [14, 15], liquid crystal reflectarrays [16], a bulky metallic 8×8 waveguide array [17], electronic BiCMOS 130 nm 2×2 phased arrays [18], and photonic-assisted [19] concepts. Table 1 summarizes these previously reported approaches for 1D and 2D beamsteering. Further details on these and other beamsteering

**Tab. 1:** Recently developed THz beamsteering.

| | Ref. | Freq. (GHz) | Technology | Antenna array (size/type) | Scan range (El./Az.) | Max. gain (dBi) | Tested for THz Comm. |
|---|---|---|---|---|---|---|---|
| 1D | [8] | 320 | Electronic, SiGe BiCMOS, 130 nm | 1×4 patch array | 24° | 12 | |
| | [9] | 140 | Electronic, CMOS 45 nm | 8×16 patch array | 80° | 21 | × |
| | [10] | 230-330 | Photonic, InP | 16 unit-cell LWA | 88° | 11 | × |
| | [11] | 300 | Photonic, SiO2/Si3N4/InP | 1×4 bow-tie array | 62° | 10 | |
| | [12] | 150-900 | Micro-electromechanical systems (MEMS) | Metallic cantilevers array | 40° | N/A | |
| | [13] | 1100 | Graphene | 2×2 patch array | 60° | 7 | |
| 2D | [14] | 270-330 | Variable structure | Trajectory deflection of leaky-mode | 15°/20° | 23 | |
| | [15] | 140 | Metasurface | Accordion-shaped metal gratings | 20°/360° | N/A | |
| | [16] | 115 | Liquid crystal | Reflectarray | 20°/20° | 16.55 | |
| | [17] | 220-330 | Metallic waveguide | 8×8 WG array | 50°/45° | 7.5 - 17 | |
| | [18] | 318-370 | Electronic, BiCMOS, 130 nm | 2×2 phased array | 128°/53° | -6.8 dBm [1] | |
| | [19] | 230-330 | Photonic, InP | BFN with antenna array of 3 LWAs | 93°/69° | 15 | × |

[1] peak radiated power

technologies can be found in [20, 21].

To the best of our knowledge, only the solutions reported in [9, 22] were successfully utilized for THz mobile communications with 1D beamsteering. In this work, a photonic-assisted integrated chip for beamsteering in both directions, i.e. elevation and azimuth is presented and utilized for THz 6G communications with 2D beamsteering.

**Recent PICs for THz Beamsteering**

Photonic-assisted beam steering approaches have attracted much attention due to their numerous benefits, such as wide operational bandwidth and compact chip size [23]. It has been shown that transferring phase shifts (PSs) and true-time delays (TTDs) from optical to THz regime using PICs is possible. For instance, a 1×4-photomixer array with four optical delay lines (ODLs) was reported for a steering range of 35° at 600 GHz [24].

Recently, we developed optical beam-forming network (OBFN) PICs for mmW and THz beamsteering [25]. These chips use optical phase shifters based on thermo-optically controlled optical ring resonators (ORRs) for 1D beam steering at 300 GHz. By sweeping the phase difference between two adjacent THz antennas in the 1 × 4 phased array, from −120° to 120°, a beam steering range of ~62° has been demonstrated numerically at 0.295 THz [11]. In [26], we reported a PIC employing a Si-based dielectric rod waveguide (DRW) to support broadband THz communications. In [22], we reported the first mobile THz 6G communications by using an InP-based photonic-assisted 1D beamsteering chip. Here, the THz transmitter antenna was fed by a THz photodiode. Using this PIC, we were able to transmit data wirelessly at 300 GHz over a short distance of 6 cm at data rates of 24 Gbps with a total steering angle of 33° and an antenna gain of ~14 dBi.

In this work, we utilized our InP-based leaky-wave antenna technology already reported in [19] to demonstrate beamsteering in both directions, i.e., elevation and azimuth. For THz signal generation, we utilized our MUTC-PDs reported in [27] to feed the antennas via a CPW-to-MSL transition shown in Fig. 1b. The InP-based 2D beamsteering chip shown in Fig. 1c consists of an array of three leaky wave antennas (LWAs) integrated with a beam forming network named coherently radiating periodic structures (CORPS-BFN). The LWA array is responsible for steering the beam in elevation and the CORPS-BFN enables to steer the beam in azimuth direction. Details on the function of the CORPS-BFN can be found in [19].

As can be seen from Fig. 2, the measured steering angles in elevation and azimuth are 45°

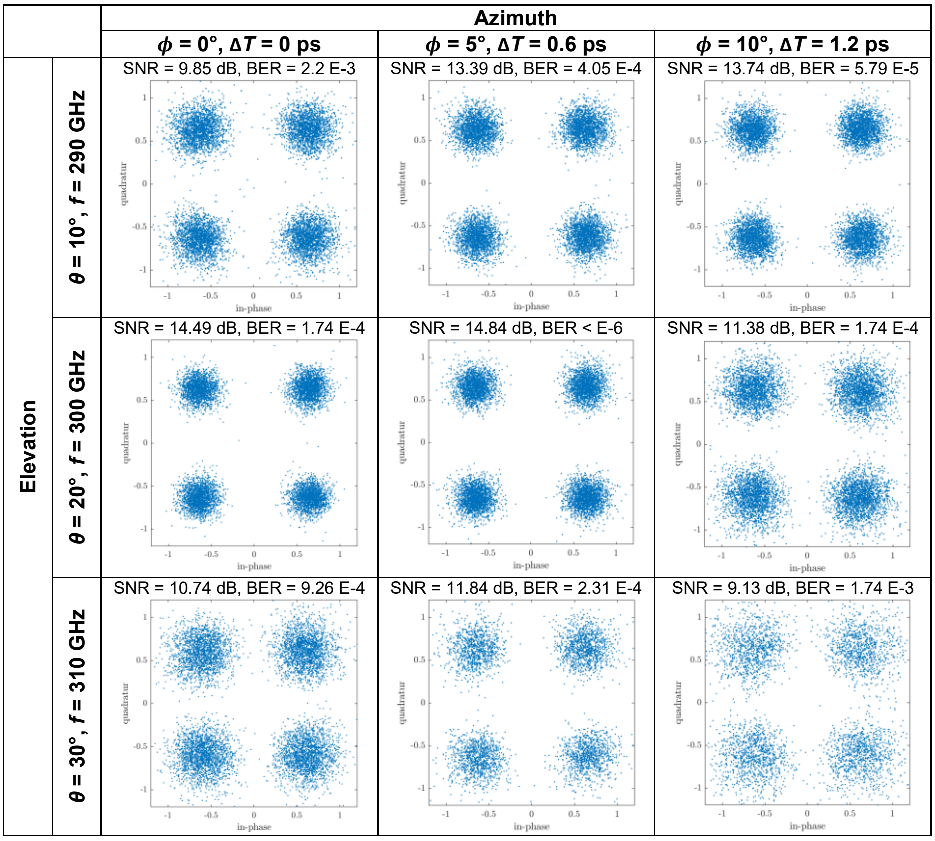


**Fig. 3:** Characterized constellation diagram at different steering angles ($\theta$, $\phi$).

and 28°, respectively. The comparison with simulated beamsteering performances reveal aa good agreement. According to theory, steering the angle in azimuth by 5° requires a time delay of 0.56 ps, which is in good agreement to the 0.6 ps measured. For tuning in elevation, the simulated steering slope of 1 °/GHz almost perfectly agrees with the measurements.

To demonstrate the functionality of the fabricated PIC, data was transmitted at different angles in azimuth (0°-10°) and elevation (10°-30°) direction. For this purpose, an IF-OFDM waveform with 1 GHz bandwidth and QPSK modulation generated by AWG was modulated onto one of the two optical carriers. The control of the beam was then realized by tuning the optical delay (azimuth direction) and the frequency (elevation direction). As in [22], an envelope detector was used as a receiver, which mixes the wirelessly transmitted signal back into the baseband. For subsequent signal analysis, the down-mixed waveform was then recorded using DSO.

As shown in Fig. 3, a bit error rate below the limit of 3.8 E-3 for 7% overhead HD-FEC could be achieved for all angles.

## Conclusion

We reported on RF and photonic beamsteering technologies for THz frequencies. A photonic-assisted chip enabling 2D beamsteering is presented. The maximum measured THz steering angels in azimuth and elevation are 45° and 28°, respectively. By employing the fabricated THz 2D beamsteering chips, mobile THz communications is demonstrated for the first time to our knowledge. For all angles, a bit error rate below the limit of 3.8 E-3 for 7% overhead HD-FEC is achieved.

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