

Review

Photonic THz Wireless Communications: Beyond Faster and Farther Link Demonstrations

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Abstract

Photonic THz wireless communications have developed primarily through point-to-point demonstrations aimed at achieving higher data rates and longer transmission distances. In this development, uni-traveling-carrier photodiodes (UTC-PDs) have played a central role by enabling optical heterodyne generation of widely tunable and modulation-transparent THz carriers. This review revisits the progress of UTC-PD-enabled photonic THz wireless links from a faster-and-farther perspective. Specifically, we first examine how representative demonstrations have pushed the performance frontier and then identify the technical factors underlying this progress, with emphasis on low-noise optical source engineering, multiplexing, and equalization-based reception. We further discuss how the same capacity-driven trend has begun to reshape the field beyond fixed point-to-point links, giving rise to laser-enabled functional expansion and array-based beam manipulation. In this context, photonic THz transmitters are increasingly viewed not only as sources of spectrally pure carriers but also as platforms for arbitrary waveform generation and spatial beam control. Taken together, recent progress in photonic THz wireless communications is less a sequence of record updates than a shift from record-oriented links toward function-oriented transmitter architectures.

Keywords: photonic THz wireless communications; uni-traveling-carrier photodiodes (UTC-PDs); frequency hopping spread spectrum (FHSS); integrated sensing and communication (ISAC); beam steering



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1. Introduction

THz communication has been recognized as a key candidate for overcoming spectrum scarcity and enabling ultra-high-capacity wireless links in future wireless systems, owing to the availability of wide bandwidths, strong directionality, and compatibility with both electronic and photonic signal-generation approaches [1–8]. Within this broader context, photonic THz wireless communications have advanced significantly over the past two decades, motivated by the combination of the vast spectral resources available in the THz band and the maturity of optical signal generation and modulation technologies. Compared with purely electronic approaches, photonic architectures provide an effective route to high-frequency wireless transmission [9–12], owing to their wide carrier tunability, direct compatibility with optical communication systems, and seamless integration of fiber and wireless links. Within this framework, uni-traveling-carrier photodiodes (UTC-PDs)

have played a central role [13–15], enabling many of the representative photonic THz wireless demonstrations reported to date. Their significance extends beyond THz carrier generation, as they also provide a flexible platform for implementing tunable, wideband, and modulation-transparent wireless links. Consequently, the evolution of photonic THz wireless communications has been closely associated with the development of UTC-PD-enabled systems.

It is also useful to position UTC-PD-based photomixing relative to other THz-generation technologies. Electronic frequency multipliers and power-amplifier front ends are increasingly mature in sub-THz bands and can offer compact electrical integration, but their frequency agility and bandwidth become more difficult to maintain at higher THz frequencies. Quantum cascade lasers (QCLs) can provide high THz output power, but their operating conditions, modulation flexibility, and system integration differ from those of fiber-compatible photonic links. Resonant-tunneling diodes (RTDs) offer compact solid-state THz oscillation, although output power and support for high-capacity modulation remain important constraints. In this comparison, UTC-PD-based photomixing occupies a distinctive position because it combines broad frequency tunability, optical modulation compatibility, and direct fiber–wireless convergence while still facing output-power and packaging limitations.

Over this period, the most visible progress has been achieved through point-to-point demonstrations targeting higher data rates and longer transmission distances [16–19]. These efforts have defined the main performance frontier and have served as the primary benchmark for subsequent advances. They have verified the capacity potential of photonic THz links and clarified the feasibility of wireless transmission beyond conventional microwave and millimeter-wave systems. At the same time, the continued pursuit of faster-and-farther transmission has revealed the technical basis of this progress, including low-noise photonic carrier generation, high-speed modulation and detection, efficient radiating interfaces, and increasingly advanced signal processing. The history of UTC-PD-enabled photonic THz wireless links is therefore not merely a series of record-breaking demonstrations but also an indication of how the underlying system architecture has matured.

Existing review articles have surveyed the field from broad technological perspectives [9–11,16–20]. However, a focused re-examination of UTC-PD-enabled photonic THz wireless links along the main line of point-to-point demonstrations remains limited. Such a perspective is useful because these demonstrations constitute the dominant route by which the field has advanced and provide a clear basis for understanding how the current performance frontier has been reached. From a broader 6G perspective, THz communication is also expected to support artificial-intelligence (AI)-assisted networking, integrated sensing, ultra-dense access, and emerging service requirements. This system context further motivates discussion beyond isolated high-speed link demonstrations [21–27]. Within this broader system context, the pursuit of higher data rates and longer transmission distances has led to closely related research directions, including beam control, real-time operation, multifunctional transmission, and system-oriented link functions. These topics arise from the technical requirements of high-capacity and high-frequency wireless transmission. They should therefore be discussed as part of the broader evolution of photonic THz wireless systems rather than being viewed only through record values of data rate and transmission distance.

In contrast to the literature focused primarily on THz device platforms and broader surveys organized by application scenario, this review makes two specific contributions. First, it interprets the faster-and-farther progress of UTC-PD-enabled links as the result of coordinated progress across the source, transmission, and reception sides, rather than as a result of photonic source improvement alone. Second, it identifies and organizes

the ongoing transition from record-oriented point-to-point links toward function-oriented transmitter architectures, in which optical-domain programmability is converted into waveform-control and beam-control functionalities.

Accordingly, this review is organized as follows. Section 2 revisits the faster-and-farther point-to-point demonstrations that define the core progress of UTC-PD-enabled photonic THz wireless communications, with emphasis on both the reported performance and the underlying technical factors. Section 3 then examines recent directions beyond the mainstream record-oriented path, focusing on laser-enabled waveform expansion and array-based beam manipulation. Finally, Sections 4 and 5 provide an outlook and summarize the main conclusions, respectively.

2. Evolution of Record Demonstrations and Their Enabling Technologies

Recent progress in photonic THz wireless links is most clearly reflected in record demonstrations targeting higher data rates and longer transmission distances. Before revisiting these system-level demonstrations in Section 2.2, Section 2.1 introduces the UTC-PD-based photonic THz transmitter as the core source architecture that converts optical-domain carrier generation into radiated THz signals. The discussion then turns in Section 2.3 to the main technical factors behind this progress, with emphasis on low-noise optical sources, multidimensional multiplexing, and receiver-side equalization.

2.1. UTC-PD-Based Photonic THz Transmitter

A UTC-PD-based photonic THz transmitter can be described by three closely connected stages, as summarized in Figure 1: (a) optical beat-note generation, (b) optical-domain modulation, and (c) optical-to-THz conversion. The first stage defines the carrier frequency. In practice, the required optical beat note can be generated using two independent lasers, sideband generation from a single laser, or two selected lines from an optical comb or multiwavelength source. These approaches differ in implementation complexity and coherence characteristics, but they share the same function: generating two optical components whose frequency spacing determines the emitted THz carrier. The second stage maps the information signal onto the optical field before THz generation. Because this stage can employ intensity modulation, phase modulation, or full in-phase/quadrature (I/Q) modulation, the transmitter can directly leverage mature optical communication formats, including on-off keying (OOK), phase-shift keying (PSK), quadrature amplitude modulation (QAM), and orthogonal frequency-division multiplexing (OFDM). In the final stage, optical heterodyning (or photomixing) of the modulated beat signal in the UTC-PD generates a THz-frequency photocurrent, which is coupled to a radiating or guiding interface such as an on-chip antenna, waveguide, or quasi-optical structure. From this perspective, the significance of a UTC-PD-based photonic THz transmitter lies not only in heterodyne carrier generation but also in the integration of carrier synthesis, advanced modulation, and output coupling within a single transmitter architecture. This integration underpins its frequency flexibility, modulation transparency, and suitability for high-capacity THz wireless links.

Among these stages, optical beat-note generation is particularly important because it directly affects the carrier tunability, phase noise, and modulation capability of the generated THz signal. Although the three beat-note generation schemes illustrated in Figure 1a share the same photomixing function, they differ in the source properties most relevant to link performance. The dual-free-running-laser scheme offers simple and wide tunability, but its weaker relative coherence can limit the use of high-order modulation formats. In contrast, single-laser sideband generation sacrifices part of the tuning flexibility in exchange for strongly correlated optical tones and reduced beat-note phase noise. Comb-

and microcomb-based sources further extend this concept by providing mutually correlated optical tones over a broad spectral range, although they generally require more complex stabilization, line selection, and system integration.

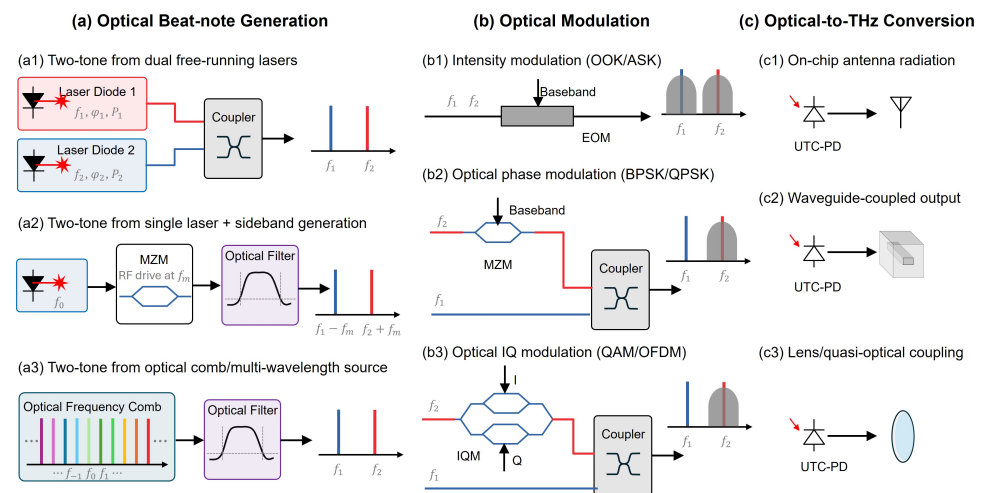


Figure 1. General architecture of a UTC-PD-based photonic THz transmitter employing optical heterodyning (photomixing) technique.

2.2. Record Demonstrations of Photonic THz Wireless Links

Recent THz wireless communication demonstrations show a clear evolution from feasibility-oriented links toward high-capacity and longer-distance transmission systems. As summarized in Figure 2, reported transmission rates have increased substantially over the past decade, with several demonstrations achieving hundreds of gigabits per second and, more recently, approaching the terabit-per-second regime, particularly in the 300–450 GHz frequency range. This trend reflects the combined progress of photonics-assisted THz generation, high-speed modulation, broadband receivers, high-order modulation formats, and advanced digital signal processing. Specifically, early demonstrations primarily focused on establishing the feasibility of photonic THz wireless transmission [28,29]. They confirmed that photonic techniques could generate and modulate THz carriers with bandwidths beyond those readily achievable by electronic approaches while supporting fiber-like data rates in short-range wireless links. Once feasibility had been established, research efforts increasingly shifted toward extending the performance frontier along two largely complementary directions.

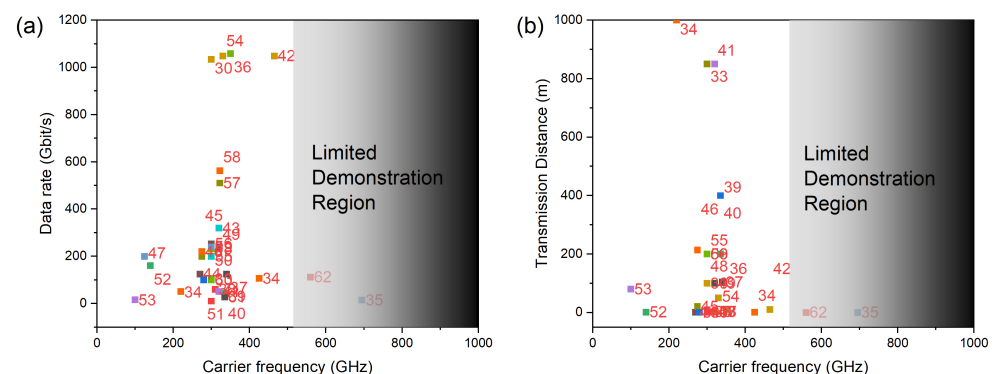


Figure 2. Distribution of representative UTC-PD-based photonic THz wireless communication demonstrations as a function of carrier frequency [30–62]. (a) Transmission rate versus frequency band. (b) Transmission distance versus frequency band.

Specifically, the first direction focused on throughput scaling through improved carrier quality, higher-order modulation formats, and, more recently, multidimensional multiplexing. This direction has now reached the terabit-per-second regime, exemplified by a 300 GHz photonic wireless link achieving an aggregated net data rate of 1.034 Tbit/s over 100 m [41], with a subsequent milestone in the 600 GHz band with a 1.04 Tbit/s transmission rate [32]. The second focused on reach extension through the combined use of high-gain antennas or dielectric lenses, favorable atmospheric transmission windows, improved receiver sensitivity, and increasingly sophisticated digital signal recovery. Recent demonstrations have extended transmission distances from several hundred meters to the kilometer scale, including a field trial of 50 Gbit/s real-time transmission over a 1 km wireless link at 220 GHz [42] and a 120 Gbit/s transmission over 850 m at 300 GHz [50]. To make this evolution more explicit, Table 1 complements the rate–distance distributions in Figure 2 by summarizing representative UTC-PD-enabled photonic THz wireless demonstrations in terms of publication year, carrier frequency, transmission distance, data rate, modulation format, transmitter architecture, multiplexing strategy, and equalization method. Beyond the chronological progression of record demonstrations, the distribution of reported results provides three useful system-level insights.

First, from the perspective of link-budget scaling, the rate–distance distribution reveals a persistent trade-off. The highest data-rate demonstrations are generally achieved over relatively short links, whereas longer transmission distances typically rely on more conservative modulation formats and tighter link-budget optimization. This observation indicates that THz wireless performance is governed not only by available bandwidth but also by the combined effects of free-space path loss, atmospheric attenuation, output power, antenna gain, receiver sensitivity, beam alignment, and signal processing capability. More specifically, this rate–distance trade-off can be understood from the link budget. Wideband, high-order modulation formats require a high received signal-to-noise ratio (SNR), whereas the limited output power of a single UTC-PD, together with free-space path loss and atmospheric attenuation, makes such an SNR increasingly difficult to maintain as the link distance increases. As a result, record data-rate demonstrations tend to be concentrated at short ranges, while long-reach links usually rely on more robust low-order modulation formats, higher-gain apertures, and favorable atmospheric transmission windows. This interpretation is also consistent with previous THz channel studies, which show that molecular absorption, frequency-selective attenuation, diffuse scattering, and highly directional propagation jointly shape the usable bandwidth, link distance, and achievable capacity of THz wireless systems [63–71]. These considerations suggest that future research is likely to place increasing emphasis on balanced system-level optimization [72–79], in which carrier frequency, bandwidth, transmission distance, spectral efficiency, link robustness, and implementation complexity are considered jointly rather than individually. Such a system-level view is also aligned with distance-aware and adaptive spectrum-allocation studies [80,81], which suggest that the usable THz bandwidth should be adjusted according to propagation distance, absorption windows, and link-budget constraints rather than being treated as a fixed resource.

Second, the carrier-frequency distribution of recent demonstrations provides additional insight into the maturity of different THz technologies. The relatively small number of record-level results reported in the 100–200 GHz range should not be interpreted as a lack of research activity. Rather, this band has gradually evolved into a technologically mature regime, where both electronic and photonic transmitter technologies are increasingly available. Recent advances in D-band power amplifiers and front-end circuits have significantly improved the capability of electronic systems, while photonic UTC-PD and MUTC-PD transmitters continue to offer broadband and frequency-agile carrier genera-

tion. Consequently, the value of photonics-assisted approaches in this frequency range increasingly lies in system-level advantages, including optical-fiber compatibility, low-loss signal distribution, frequency agility, modulation transparency, and potential integration with optical beamforming architectures. This contrast also clarifies the complementary roles of electronic and photonic signal-generation routes. Relative to electronic frequency-multiplier front ends, which currently offer higher output power and compact integration in the lower THz bands, photonic UTC-PD transmitters provide wider and more agile carrier tunability, modulation transparency, and native fiber compatibility, at the cost of lower emitted power and photomixing efficiency.

Table 1. Representative UTC-PD-enabled photonic THz wireless demonstrations and their key system-level parameters. The table compares carrier frequency, transmission distance, data rate, modulation format, multiplexing strategy, and equalization method to clarify how record link performance has been achieved.

Ref. (Year)	Carrier Frequency	Distance	Data Rate	Modulation	Multiplexing	Equalization/DSP
[30] (2018)	425 GHz	0.5 m	106 Gbit/s	16QAM	SISO	Offline + MMA
[31] (2020)	695 GHz	0.01 m	14.5 Gbit/s	OOK	SISO	Online w/o Eq.
[33] (2021)	350 GHz	10 m	1.059 Tbit/s	16QAM	WDM + SISO	Offline DSP
[34] (2021)	340 GHz	54/104 m	124.8/44.8 Gbit/s	PS-256QAM/PS-64QAM	SISO	Offline + CMA + Volterra + DD-LMS
[35] (2021)	310 GHz	3 m	60 Gbit/s	PAM-4	SISO	Offline + Volterra-DFE
[36] (2022)	335 GHz	400 m	30.12 Gbit/s	OFDM-16QAM	SISO	Offline + Volterra
[37] (2022)	335 GHz	200 m	44 Gbit/s	PS-64QAM	SISO	Offline + LBS-RDE + VNLE
[38] (2023)	320 GHz	850 m	50 Gbit/s	16QAM	SISO	Offline + Volterra
[39] (2023)	370/465 GHz	10 m	1.0488 Tbit/s	PS-64QAM	PDM + 2 × 2 MIMO	Offline + VQ-VAE
[40] (2023)	320 GHz	3 m	320 Gbit/s	PDM-16QAM	PDM + 2 × 2 MIMO	Offline + SCFDE + DD-LMS
[41] (2024)	300 GHz	100 m	1.034 Tbit/s	64QAM	WDM + 4 × 1 MISO	Offline DSP
[42] (2024)	220 GHz	1 km	50 Gbit/s	PDM-16QAM	PDM + SISO	Online ZF-FDE
[43] (2024)	270 GHz	0.5 m	125 Gbit/s	32QAM	SISO	Online DSP
[44] (2024)	275 GHz	20 m	200 Gbit/s	32QAM	SISO	Online DSP
[45] (2024)	275 GHz	214 m	220 Gbit/s	32QAM	SISO	Online DSP
[46] (2024)	125 GHz	4.6 km	200 Gbit/s	16QAM	PDM + 2 × 2 MIMO	Offline + CMA + VNLE
[47] (2024)	300 GHz	200 m	232 Gbit/s	QPSK	PDM + 2 × 2 MIMO	Offline + Cascaded LE + VNE
[48] (2024)	320 GHz	100 m	240 Gbit/s	QPSK/16QAM	PDM + 2 × 2 MIMO	Offline + CVNN
[49] (2024)	300 GHz	0.5 m	10 Gbit/s	OOK	SISO	Online w/o Eq.
[50] (2025)	300 GHz	850 m	104 Gbit/s	16QAM	PDM + 2 × 2 MIMO	Offline + VNLE
[51] (2025)	280 GHz	25 cm	100 Gbit/s	16QAM/32QAM	Offline DSP	
[52] (2025)	140 GHz	1 m	160 Gbit/s	16QAM	SISO	Offline DSP
[53] (2025)	100 GHz	80 m	16.14 Gbit/s	16/64QAM	BiDi	Online DSP
[54] (2025)	280/330 GHz	50 m	1.0488 Tbit/s	PS-64QAM/16QAM	SISO	Offline + VNLE
[55] (2025)	300 GHz	200 m	200 Gbit/s	QPSK	PDM + 2 × 2 MIMO	Offline + 2D-CNN
[56] (2025)	300 GHz	200 m	253 Gbit/s	PS-16QAM DP-OFDM	PDM + 2 × 2 MIMO	Offline + 4 × 4 Offline + TFPD-TMP-NLE
[57] (2025)	322 GHz	3 m	510 Gbit/s	PS-64QAM	PDM + 2 × 2 MIMO	Offline + MIMO-ICP-eAPR
[58] (2025)	322 GHz	3 m	562.5 Gbit/s	64QAM	PDM + 2 × 2 MIMO	Offline + MIMO-LMS/CPE
[59] (2026)	300 GHz	200 m	240 Gbit/s	9QAM	PDM + 2 × 2 MIMO	CMMA-NAG + MIMO-VNLE
[60] (2026)	300 GHz	200 m	100 Gbit/s	QPSK	PDM + 2 × 2 MIMO	Offline + DB-UACNN + MLS
[61] (2026)	335 GHz	2.2 km	27.84 Gbit/s	16QAM	1 × 2 SIMO	Offline + LSTM-ANN
[62] (2026)	560 GHz	0.01 m	112 Gbit/s	16QAM	SISO	MRC + Volterra
						Online w/o Eq.

Abbreviations: SISO: single-input single-output; SIMO: single-input multiple-output; MISO: multiple-input single-output; MIMO: multiple-input multiple-output; PDM: polarization-division multiplexing; WDM: wavelength-division multiplexing; PS: probabilistically shaped; OOK: on-off keying; QAM: quadrature amplitude modulation; PAM: pulse-amplitude modulation; OFDM: orthogonal frequency-division multiplexing; DSP: digital signal processing; Eq.: equalization; MMA: multimodulus algorithm; CMA: constant modulus algorithm; DFE: decision-feedback equalizer; FDE: frequency-domain equalizer; ZF-FDE: zero-forcing frequency-domain equalizer; SCFDE: single-carrier frequency-domain equalizer; DD-LMS: decision-directed least-mean-square; LBS-RDE: likelihood-based selection radius-directed equalizer; VNE and VNLE: Volterra nonlinear equalizer; CVNN: complex-valued neural network; CNN: convolutional neural network; MRC: maximum-ratio combining; MLS: maximum-likelihood sequence detection; CPE: carrier phase estimation; LSTM-ANN: long short-term memory artificial neural network; TFPD-TMP-NLE: time-frequency-polarization-domain trigonometric-memory-polynomial nonlinear equalizer.

Finally, at the upper end of the THz spectrum, the frequency range above 500 GHz remains comparatively underexplored and continues to represent a major opportunity for future THz wireless research. Although substantially wider bandwidths become available in this regime, practical deployment is constrained by limited transmitter power, increased propagation loss, the lack of mature high-power amplification technologies, and the difficulty of realizing low-noise receiver front ends. Recent demonstrations beyond 350 GHz, including photonic wireless transmission at 560 GHz using soliton microcombs, have illustrated the ability of photonic techniques to extend carrier generation beyond the practical limits of conventional electronics. At the same time, they highlight persistent challenges associated with photomixing efficiency, phase noise, output power, and receiver sensitivity. Progress beyond 500 GHz will therefore depend on advances in high-power photonic emitters, efficient amplification technologies, low-noise receivers, high-gain antennas, and system-level integration.

2.3. Enabling Technologies Behind Record Performance

The record demonstrations reviewed above have emerged from the convergence of multiple enabling technologies rather than from a single device-level breakthrough. As illustrated in Figure 3, progress in photonic THz wireless communications has relied on advances spanning photomixing devices [82,83], modulation formats [84,85], antennas [86–88], quasi-optical components [89–91], receiver architectures [92,93], synchronization techniques, forward error correction, equalization, multiplexing, and fiber–wireless integration [94–97]. A comprehensive review of all these technologies is beyond the scope of this article. Instead, the following discussion focuses on three representative factors that have played a particularly important role in defining the faster-and-farther performance frontier: low-noise photonic carrier generation, multiplexing, and equalization. Low-noise carrier generation is closely linked to the photonic nature of UTC-PD-based THz transmitters and directly influences spectral purity. Multiplexing and equalization, while not unique to THz communications, have evolved in distinctive ways as transmission rates and carrier frequencies continue to increase. Together, these three aspects provide a useful framework for understanding how recent record demonstrations have been achieved and where future performance improvements are likely to originate.

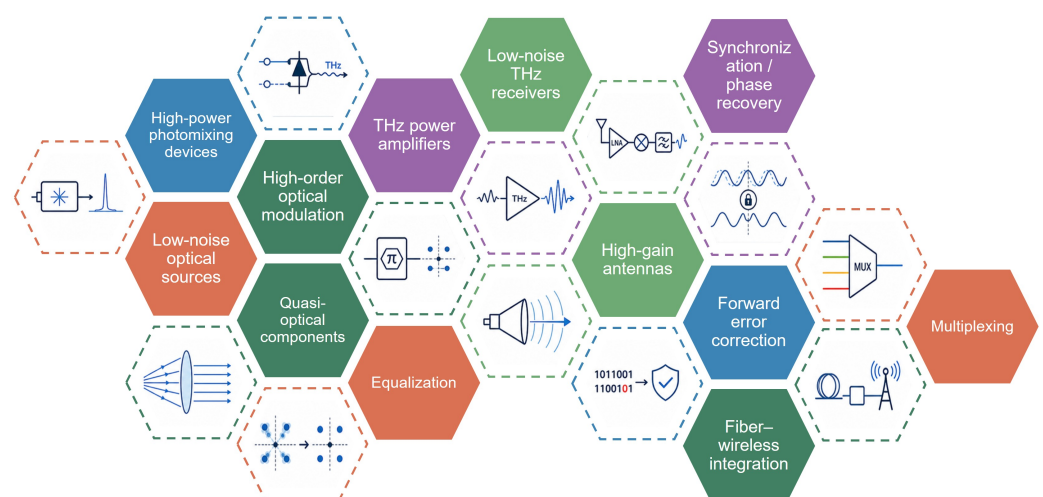


Figure 3. Representative enabling technologies underlying recent progress in photonic THz wireless communications.

2.3.1. Low-Noise Optical Sources

Low-noise photonic THz generation is not determined by a single optical-source architecture but by how effectively the relative phase noise between the two optical tones can be suppressed before photomixing. Since the THz carrier generated in a UTC-PD is given by the optical beat note, its phase noise is governed primarily by the relative phase fluctuation between the two optical components rather than by their absolute optical linewidths alone. As shown in Figure 1(a1), the simplest implementation employs two independent narrow-linewidth lasers. This approach provides broad frequency tunability and a relatively straightforward transmitter architecture, but the two lasers generally exhibit largely uncorrelated phase fluctuations. As a result, the beat-note linewidth and phase noise become increasingly problematic for high-order modulation formats and high-spectral-efficiency THz links.

A more robust route is to generate the two optical tones from a common coherent source. For example, sideband generation from a common master laser using a Mach–Zehnder modulator or a phase modulator followed by optical filtering can provide two optical components whose common laser phase noise is largely correlated, as illustrated in Figure 1(a2). In this case, the relative phase noise is mainly determined by the radio-frequency (RF) drive source and the modulation/filtering process, rather than by two independent optical oscillators. Optical-frequency-comb and microcomb approaches [98–101] extend this concept further by providing a set of mutually phase-related optical lines over a broad spectral range, as shown in Figure 1(a3). By selecting two comb lines with the desired frequency spacing and photomixing them in a UTC-PD, low-phase-noise THz carriers can be generated with wide frequency coverage and high spectral purity. Recent Kerr-comb and packaged microcomb sources therefore represent an important direction for compact, low-noise photonic THz transmitters [102–105]. The phase-noise characteristics of these photonic THz generation schemes influence the modulation formats and spectral efficiencies that each source architecture can practically support, as summarized in Table 2.

Table 2. Comparison of low-noise photonic THz generation schemes and phase-locking techniques. The table summarizes the source or locking category, generated frequency, phase-noise performance, phase-noise floor, and linewidth as key metrics for evaluating carrier spectral purity.

Ref.	Tech Category	Frequency	Phase Noise @ 10 kHz	Phase-Noise Floor	Linewidth
[98]	Electro-optic OFC	80–320 GHz	−100 dBc/Hz	N.G.	N.G.
[99]	Injection-locked gain-switched laser comb	192 GHz	N.G.	N.G.	115 kHz
[100]	OEO-driven OFC	101.5 GHz 242.6 GHz	−90 dBc/Hz −78 dBc/Hz	N.G.	N.G.
[101]	Mode-locked fiber laser comb	1 THz	−105 dBc/Hz	N.G.	<1 Hz
[102]	Kerr microresonator soliton comb	560 GHz	−60 dBc/Hz	N.G.	N.G.
[103]	FFPR Kerr comb	300 GHz	−95 dBc/Hz	−133 dBc/Hz	72.2 mHz
[104]	Fiber-referenced Kerr comb	560 GHz	−99 dBc/Hz	−108 dBc/Hz	N.G.
[105]	DKS comb	300 GHz	−100 dBc/Hz	N.G.	N.G.
[106]	OIL + EO-comb	80 GHz	N.G.	N.G.	100 kHz
[107]	OIL + Kerr microresonator soliton comb	>100 GHz	−104 dBc/Hz	N.G.	N.G.
[108]	OIL + MLL-based OFC	408 GHz	≈ −65 dBc/Hz	N.G.	N.G.
[109]	OIL + DKS comb	300 GHz	−95 dBc/Hz	N.G.	N.G.
[110]	Optical feedback locking + V-shaped cavity	0.1–1.4 THz	N.G.	−118 dBc/Hz	N.G.
[111]	DWBL + molecular rotational transition	300 GHz–3 THz	< −60 dBc/Hz	N.G.	N.G.
[112]	OPLL + comb line	10–300 GHz	−80 dBc/Hz	N.G.	<1 kHz

Abbreviations: OFC: optical frequency comb; OEO: optoelectronic oscillator; OIL: optical injection locking; OPLL: optical phase-locked loop; DKS: dissipative Kerr soliton; FFPR: fiber Fabry–Perot resonator; DWBL: dual-wavelength Brillouin laser; N.G.: not given.

In addition to generating mutually coherent tones directly from a common source, another class of techniques establishes the required relative phase coherence by locking otherwise noisy optical oscillators to a common or external frequency reference. From

this viewpoint, optical injection locking (OIL) [106–109], common-cavity optical-feedback locking [110,111], and optical phase-locked loops (OPLLs) [112] can all be regarded as reference-based coherence-transfer techniques, although their physical locking mechanisms are different. In OIL, as shown in Figure 4, an external optical field is injected into slave lasers, forcing each slave laser to oscillate coherently with the corresponding master tones within a finite locking range. When two slave lasers are injection-locked to two selected lines of the same optical frequency comb, the comb serves as a mutually phase-correlated optical reference. This suppresses the independent phase fluctuations of the two free-running lasers and reduces the relative phase noise of the optical beat note before photomixing. In contrast, an OPLL detects the heterodyne phase error between a slave laser and a master laser or comb line and then uses an electronic feedback loop to control the slave laser frequency or phase. Common-cavity optical-feedback locking follows the same reference-based principle in a broader sense but uses the resonance modes of a high-finesse optical cavity as the frequency reference; when two lasers are locked to different modes of the same cavity, common-mode cavity fluctuations can be partially cancelled in the difference frequency. These stabilization techniques do not change the fundamental UTC-PD photomixing process but improve the linewidth, frequency stability, and spectral purity of the generated THz carrier by stabilizing the optical beat note in advance.

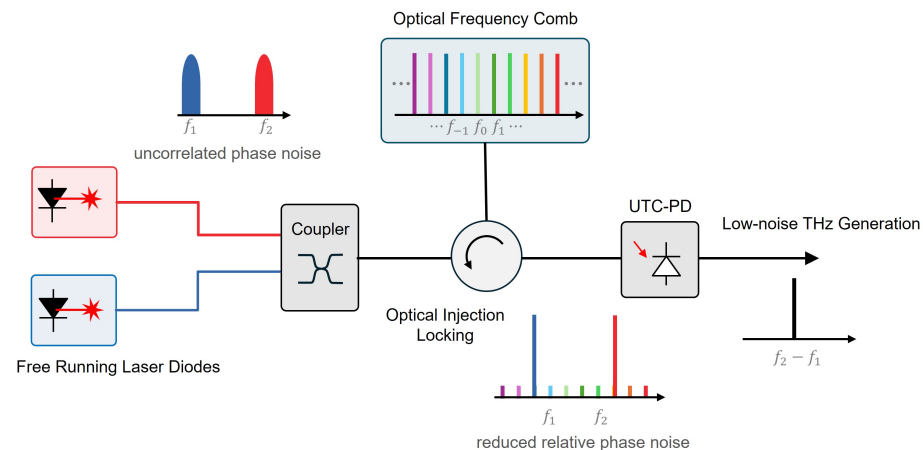


Figure 4. Schematic of OIL-assisted photonic THz generation using two free-running lasers injection-locked to selected OFC lines, thereby reducing the relative phase noise of the optical beat note. Representative reported performance after locking [108] includes a 10 dB improvement in optical SNR, a reduction in the 3 dB heterodyne linewidth from the sub-GHz scale to the hertz level, and phase noise below -100 dBc/Hz at offset frequencies above 1 MHz for injection powers exceeding 9 dBm.

2.3.2. THz Multiplexing

Once a single channel approaches the practical limits imposed by modulator bandwidth, UTC-PD output power, and receiver sensitivity, further capacity scaling increasingly depends on multiplexing. Although multiplexing itself is not unique to THz communications, it has become one of the main approaches for converting the wide but difficult-to-utilize THz spectrum into large usable line rates. Among the available multiplexing dimensions, frequency multiplexing is the one most naturally aligned with the UTC-PD transmitter architecture. When multiple optical tones, comb lines, or parallel optical beat-note branches are available, the same photonic transmitter architecture can generate multiple THz carriers or subchannels simultaneously. In this sense, frequency multiplexing is less an externally added transmission layer than a direct extension of photonic carrier generation itself.

The evolution from early single-channel demonstrations to later aggregate-capacity systems illustrates this transition clearly. For example, early 0.4 THz photonic wireless links demonstrated transmission rates on the order of 100 Gbit/s using a single carrier channel [30], whereas later systems entered the terabit-per-second regime through multi-dimensional multiplexing built around a common photonic source architecture. A representative example is the 300 GHz photonic wireless transmission system achieving a net data rate of 1.034 Tbit/s over 100 m by combining frequency-, polarization-, and spatial-division multiplexing, rather than by scaling the throughput of a single UTC-PD channel alone [41]. These examples also show that the different multiplexing dimensions should not be treated as equivalent. Frequency multiplexing can scale aggregate capacity through multiple usable subcarriers but requires sufficient optical-source bandwidth, front-end bandwidth, and channelization control. Polarization multiplexing can nominally double spectral efficiency without additional bandwidth but requires dual-polarized THz apertures and 2×2 equalization to suppress cross-polarization leakage. Spatial multiplexing can add parallel streams only when the wireless channel provides sufficient rank, which is difficult to guarantee in highly directive line-of-sight THz links. Therefore, the physical origin of the multiplexing gain should be distinguished when comparing high-capacity THz demonstrations.

Among these dimensions, polarization multiplexing requires particular care in UTC-PD-based photonic THz systems because the optical polarization state is not directly transferred to the generated THz carrier. In a UTC-PD, optical-to-electrical conversion is governed by square-law photodetection, and the polarization of the emitted THz wave is determined primarily by the radiating interface, including the antenna structure and output coupling configuration. Consequently, polarization multiplexing must be established at the THz transmitter and receiver level rather than inherited directly from the optical domain. Nevertheless, it remains attractive because it introduces an additional transmission dimension without proportionally increasing the occupied bandwidth. This capability was demonstrated early in photonics-aided 2×2 MIMO THz transmission systems [113].

This difference between polarization-based parallel transmission and spatial MIMO is particularly important when interpreting recent photonics-enabled THz wireless demonstrations. In conventional wireless communications, MIMO usually refers to spatial multiplexing, where the multiplexing gain is determined by the rank, condition number, and spatial diversity of a spatially dispersive channel matrix [114–116]. In contrast, many THz links operate under highly directive quasi-optical line-of-sight conditions, where the channel does not necessarily provide rich spatial scattering. In such cases, multiple data streams are often separated mainly by orthogonal polarization states or by carefully aligned beam paths, and the 2×2 equalizer is primarily used to compensate polarization coupling, imbalance, and residual inter-channel interference rather than to exploit a rich spatial MIMO channel.

For this reason, the term “MIMO” is used in this review with attention to the underlying propagation and multiplexing mechanism. When the parallel streams are supported by the rank and conditioning of a spatially dispersive channel matrix, the link is referred to as spatial MIMO. When the streams are mainly separated by orthogonal THz polarizations over a quasi-optical line-of-sight path, the configuration is more accurately described as dual-polarization or polarization-division multiplexing assisted by 2×2 equalization. This classification is useful when comparing recent high-capacity photonics-enabled THz wireless demonstrations [46,47,59,60,117,118]. Although these systems represent important progress toward high-capacity THz wireless transmission, their capacity enhancement may originate from different mechanisms, including frequency multiplexing, polarization-division multiplexing, diversity reception, beam-domain multiplexing, or conventional

spatial MIMO. As illustrated in Figure 5, distinguishing these mechanisms helps clarify whether the reported performance reflects true spatial multiplexing gain or another form of parallel-channel transmission.

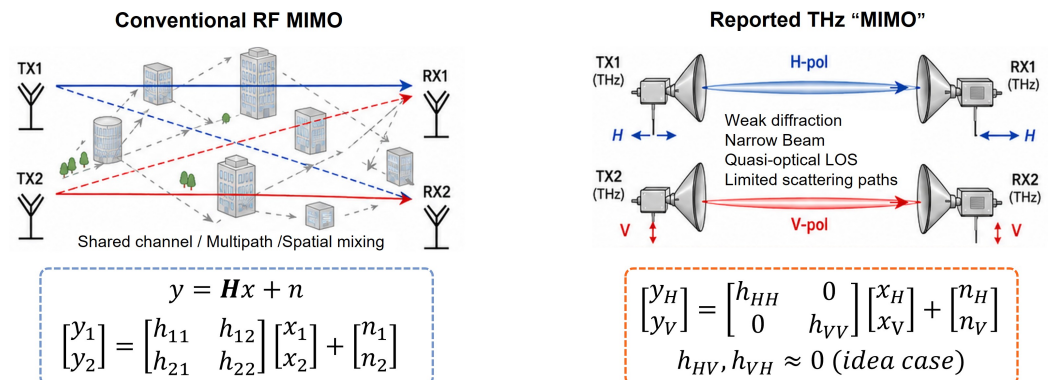


Figure 5. Conceptual comparison between conventional RF spatial MIMO and polarization-dominant THz “MIMO” links reported in recent photonic THz wireless demonstrations.

2.3.3. Equalization

As photonic THz systems move toward higher baud rates, higher-order modulation formats, longer wireless transmission distances, and multidimensional multiplexing, receiver-side equalization becomes a central part of link design. Strictly speaking, equalization is not a technique unique to THz communications, nor does it directly manipulate the radiated THz carrier in free space. In most reported systems, it is implemented after THz-to-electrical down-conversion using intermediate-frequency or baseband digital signal processing.

Its importance in photonic THz wireless links therefore arises not from the THz band itself but from the severe bandwidth limitations, frequency-selective fading, phase instability, device nonlinearity, and imperfect channel orthogonality that become unavoidable in high-capacity THz demonstrations. These impairments progressively reduce the effective decision margin of the received constellation and limit the usable bandwidth and spectral efficiency enabled by photonic THz transmission. Under such conditions, equalization is no longer a secondary post-processing step but one of the practical enabling technologies that determines the experimentally achievable data rate, modulation order, and transmission distance. Figure 6 summarizes representative equalization strategies adopted in recent THz wireless systems, ranging from conventional linear equalization and decision-feedback equalization (DFE) to Volterra-based nonlinear equalization, neural-network-assisted equalization, and hybrid cascaded structures. The evolution of these methods reflects the increasing complexity of distortion mechanisms encountered in high-capacity photonic THz links.

This evolution can first be seen in early UTC-PD-based sub-THz demonstrations, where blind equalization using the constant modulus algorithm (CMA) was employed to stabilize wideband signal recovery in the 220–280 GHz range [40,119,120]. At this stage, equalization primarily compensated linear channel distortion and receiver imperfections. It became much more critical once photonic THz systems began targeting high-order modulation over extended wireless distances. A representative example is the 335 GHz 200 m photonics-aided wireless transmission of 10 GBaud probabilistically shaped 64QAM, where a likelihood-based selection radius-directed equalizer (LBS-RDE) [37] was required to sustain a net rate of 44 Gbit/s.

The role of equalization becomes even more explicit in multiplexed THz systems. In such links, increased throughput is achieved by introducing additional transmission dimensions, but these dimensions also introduce channel coupling and inter-stream in-

interference that must be compensated at the receiver. This behavior is evident in the 320 GHz photonics-aided THz-over-fiber system employing a low-complexity MIMO single-carrier frequency-domain equalizer (SCFDE), where equalization was used to demultiplex polarization-division-multiplexed signals after 20 km fiber transmission and a 3 m 2×2 MIMO wireless link, enabling 320 Gbit/s/ λ operation [40]. A similar system logic appears in the 300 GHz outdoor 200 m 2×2 MIMO demonstration, where cascaded linear equalization and MIMO Volterra nonlinear equalization (MIMO-VNE) compensated both linear and nonlinear multichannel impairments to support beyond-200 Gbit/s transmission [47].

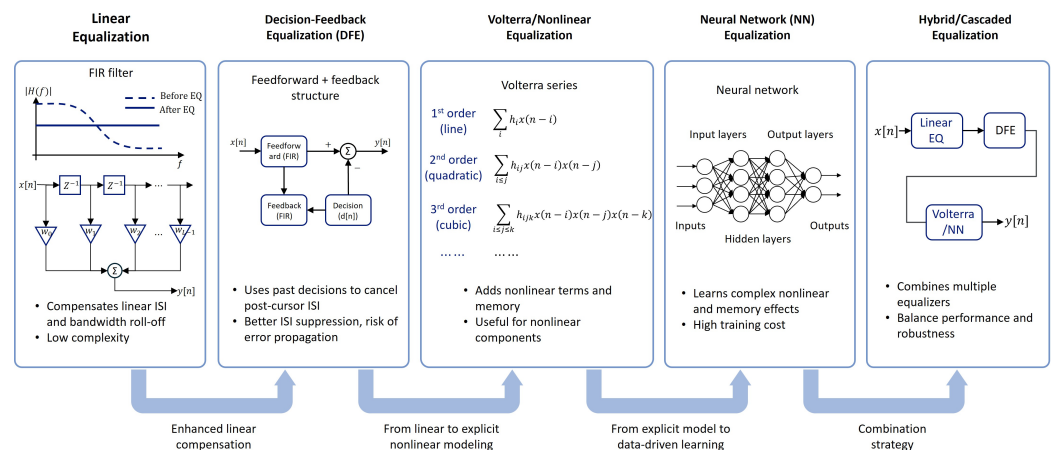


Figure 6. Representative equalization techniques for THz wireless communication systems.

More recently, this trend has extended to neural-network-assisted receivers. As operating conditions become increasingly demanding, the distortion landscape becomes difficult to capture using simple analytical channel models alone. Consequently, neural-network equalizers capable of learning the joint structure of temporal distortion, polarization crosstalk, MIMO coupling, and device nonlinearity have attracted growing attention. Complex-valued neural-network (CVNN)-based space-time equalization has been demonstrated at 320 GHz for 60 GBaud PDM-QPSK and 30 GBaud PDM-16QAM transmission over 100 m [48]. Similarly, iteratively pruned CNN equalizers have been applied to 300 GHz 200 Gbit/s outdoor 2×2 MIMO links to jointly compensate polarization crosstalk and temporal nonlinearities [55].

From an implementation perspective, these equalization methods involve different trade-offs between compensation capability and computational complexity. Linear equalizers and CMA-type blind equalizers are attractive for relatively simple channel distortion because of their low implementation complexity, but they are insufficient when nonlinear device response, polarization coupling, or MIMO interference becomes dominant. DFE and frequency-domain equalizers improve inter-symbol-interference compensation with moderate complexity, while Volterra and MIMO nonlinear equalizers provide stronger nonlinear compensation at the cost of rapidly increasing computational burden. Neural-network-based equalizers offer flexible data-driven compensation of coupled temporal and nonlinear impairments, but their training overhead, hardware implementation cost, and generalization under time-varying channels remain important limitations for real-time deployment.

Taken together, these demonstrations indicate that equalization in photonic THz systems has evolved from post-processing compensation into an enabling condition for experimentally realizing high-capacity THz wireless links. However, many reported demonstrations still rely heavily on offline digital signal processing. Therefore, the next challenge is not only to improve compensation capability but also to translate advanced equalization into low-latency, hardware-efficient, and real-time receiver implementations.

3. Emerging Trends Beyond Point-to-Point Links

The record demonstrations reviewed above established UTC-PD-based photonic THz wireless links as a viable platform for ultra-high-capacity transmission, with progress driven largely by improvements in carrier purity, multiplexing, and receiver-side signal recovery. However, these advances remained primarily within the framework of fixed point-to-point links. More recent research has gradually shifted attention from transmission performance alone toward the controllability and functionality of the photonic THz transmitter itself. In this context, photonic THz systems are increasingly viewed not only as platforms for extending data rate and transmission distance but also as reconfigurable architectures in which optical-domain programmability and radiating-aperture control can be translated into additional communication and signal-generation functionalities.

3.1. Laser-Enabled Functional Expansion

Conventional UTC-PD-based photonic THz transmitters are generally designed to maintain a stable optical beat note so that the generated THz carrier remains low-noise and compatible with high-order modulation. More recent work, however, has increasingly explored laser-frequency control not as a disturbance to be minimized but as a mechanism for waveform generation itself. Because photomixing follows $f_{\text{THz}} = |f_1 - f_2|$, controlled variation of the optical frequencies is directly mapped into the THz domain.

As illustrated in Figure 7, this capability allows the UTC-PD-based transmitter to operate not only as a single-carrier source but also as a programmable THz waveform generator. Within this framework, two representative directions have emerged. One is photonic THz frequency-hopping spread spectrum (FHSS) transmission for secure communication, in which the THz carrier is reconfigured in a pseudo-random manner according to a predefined hopping sequence. The other is THz integrated sensing and communication (ISAC) [121–123], where the carrier frequency evolves in an ordered form [124–126], for example, through frequency-modulated continuous-wave (FMCW) operation, linear frequency modulation (LFM), triangular sweeps, or more general chirp-based waveforms for joint sensing and communication. Although these approaches target different system functions, they rely on the same underlying mechanism: the frequency programmability of the optical domain is directly inherited by the generated THz carrier.

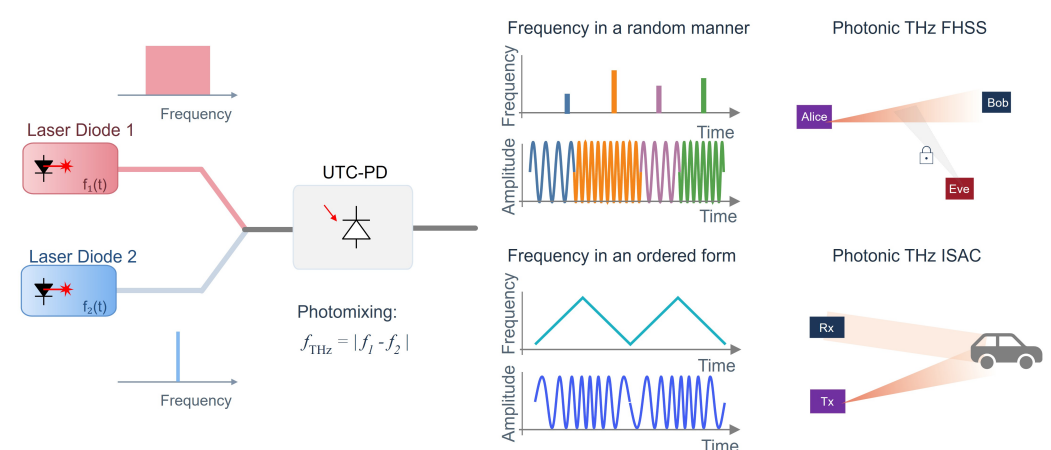


Figure 7. Laser-enabled functional expansion in UTC-PD-based photonic THz transmitters, illustrating pseudo-random carrier hopping for secure communication and ordered frequency sweeping for integrated sensing.

3.1.1. Photonic THz FHSS

Although the high directivity of THz waves provides stronger spatial confinement than microwave or millimeter-wave transmission, THz links still face important security

threats. For example, an attacker can launch jamming from a sidelobe direction toward the receiving antenna and disrupt the link [127,128]. This vulnerability is particularly relevant to noncoherent THz receivers. When the frequency offset Δf between the jammer and the legitimate carrier falls within the receiver output bandwidth, square-law detection produces a beat component in the baseband, making beat jamming effective.

In this context, the significance of laser-enabled THz FHSS lies not merely in transplanting classical FHSS spread-spectrum concepts to a higher frequency band but in creating a spectral-domain defense mechanism suited to the vulnerability of noncoherent THz receivers [129]. The anti-jamming value of FHSS is therefore strongly linked to the hop interval relative to the receiver output bandwidth, and the defining advantage of photonics-based THz FHSS is that its hopping span can be made much wider than that of frequency-multiplier-based electronic sources.

The reported hardware progression illustrates this advantage clearly. Early systems based on dual distributed-feedback (DFB) lasers established the feasibility of THz FHSS in the 110–170 GHz range [130]; tunable DFB laser arrays then moved FHSS into the 300 GHz band with 10 carriers and hopping rates of 100 hops/s [131]; optical injection locking improved controllability and enabled six carriers with 5 GHz spacing and 2.5 Gbit/s OOK communication [132]; and reflection-type transversal-filter (RTF) lasers [133–135] extended the hop interval to 40 GHz, increased the hopping rate to 25 Mhops/s, and enabled real-time OOK operation [136,137]. In practical terms, a 40 GHz hop interval already exceeds the output bandwidth of common Schottky-barrier-diode- or Fermi-level-managed barrier-diode (FMBD)-based THz receivers, giving this architecture a direct anti-jamming advantage [138–140]. These results show that the UTC-PD platform can inherently combine wide-span carrier reconfiguration with security-oriented link functionality.

This hardware evolution also clarifies the scalability limits of laser-enabled THz FHSS. The practical limit is set less by the nominal number of available carriers than by the hop interval relative to the receiver output bandwidth, together with the switching speed, settling behavior, and frequency accuracy of the tunable source. Although reflection-type transversal-filter lasers have enabled wide-interval and high-speed hopping with real-time OOK operation, higher-order modulation during hopping remains constrained by settling time, residual frequency error, and phase stability. Table 3 summarizes these representative photonic THz FHSS demonstrations in terms of carrier band, optical tuning scheme, number of carriers, hop interval or span, hopping rate, and communication format.

Table 3. Quantitative comparison of representative photonic THz FHSS demonstrations. The table highlights the optical tuning scheme and frequency-agility metrics, including transition time, number of carriers, hop interval, hopping rate, and communication format.

Ref.	Frequency Band	Optical Tuning Scheme	Transition Time	Number of Carriers	Hop Interval	Hopping Rate	Communication Format
[130]	110–170 GHz	Dual DFB lasers	N.G.	Sweep	Sweep	0.15–131.5 GHz/s	6 Gbit/s OOK
[131]	288–311 GHz	DFB laser array	0.8 ms	10	2–8 GHz	100 hops/s	5 Gbit/s OOK
[132]	115–140 GHz	EO-comb + OIL	62 μ s	6	5 GHz	N.G.	2.5 Gbit/s OOK
[136]	230–310 GHz	RTF laser	<7 ns	3	40 GHz	25 Mhops/s	500 Mbit/s 2-FSK
[137]	240–320 GHz	RTF laser	<49 ns	3	40 GHz	5 Mhops/s	10 Gbit/s OOK

Abbreviations: DFB: distributed-feedback; EO: electro-optic; OIL: optical injection locking; RTF: reflection-type transversal-filter; FSK: frequency-shift keying; OOK: on–off keying; N.G.: not given.

3.1.2. Photonic THz ISAC

THz ISAC represents an important extension of photonic THz transmitters from fixed-carrier data transmission toward programmable waveforms and carrier-frequency evolution. Two distinct implementation routes can be identified. The first route relies

on system-level integrated waveform design, in which sensing-oriented swept or spread waveforms are first generated in the baseband or intermediate-frequency domain and then modulated onto an optical carrier for UTC-PD-based photomixing [141–145]. In this approach, the optical heterodyne architecture mainly provides the THz carrier and broadband frequency translation, whereas the ISAC functionality is determined by the electrically or digitally generated integrated waveform. Such systems have demonstrated communication-sensing operation in the 300 GHz band, including high-speed data transmission, centimeter-level range resolution, and quantitative evaluation of trade-offs among chirp bandwidth, data rate, and signal power.

The second route, which is more directly connected to laser-enabled THz waveform control, uses high-speed wavelength-tunable lasers as source-level frequency actuators, such as DFB [146] or RTF laser [147]. Instead of first generating a low-frequency chirp and then translating it to the THz band, the optical frequency of a tunable laser is swept directly, for example, by applying a time-varying current to the tuning section of the laser. When this swept optical tone is heterodyned with another fixed optical tone in a UTC-PD, the optical frequency difference is directly converted into a swept THz carrier. In other words, the THz FMCW waveform is produced by tuning the optical beat frequency itself. This approach can simplify the transmitter architecture, potentially eliminating the need for external modulators or complex waveform generation using an arbitrary waveform generator (AWG). Its performance, however, becomes strongly dependent on the tuning speed, sweep linearity, frequency accuracy, and phase stability of the wavelength-tunable laser.

This source-level approach also clarifies why the development of suitable laser sources is central to future photonic THz ISAC systems. Recent demonstrations using high-speed tunable lasers have progressed from integrated THz FMCW radar and FSK communication to simultaneous fast-swept FMCW radar and high-speed wireless transmission using a single UTC-PD. Beyond the demonstrated ISAC systems discussed above, this source-level route requires laser sources with wider tuning ranges, faster sweep rates, higher output power, and lower relative phase noise. Tunable DFB laser arrays are attractive for multichannel operation and improved output power [148–153]. Distributed Bragg reflector (DBR) lasers provide flexible wavelength tuning and may support complex chirped, stepped-frequency, or multisegment ISAC waveforms [154,155]. Dual-wavelength lasers, especially those formed by monolithically integrating two DFB lasers on the same substrate, can reduce relative phase noise and simplify optical beat-note generation [156–161]. Tunable vertical-cavity surface-emitting lasers (VCSELs) are also relevant because of their fabrication scalability and energy efficiency, which may make them useful for compact photonic THz ISAC transmitters [162–166].

In short, the main value of photonic THz ISAC lies in functional waveform integration rather than in data transmission or sensing alone. In the first route, ISAC functionality is mainly created by digitally or electrically generated integrated waveforms that are translated to the THz band through photonic up-conversion. In the second route, ISAC functionality is created more directly through optically controlled carrier evolution, where the optical beat frequency itself determines the swept THz waveform. In both cases, the same photonic THz front end can support communication and range-resolved sensing, while the main scaling constraints arise from the joint bounds on chirp or sweep bandwidth, data rate, signal power, waveform stability, and frequency-control accuracy. To clarify the different design choices and performance trade-offs, Table 4 summarizes representative photonic THz ISAC demonstrations in terms of frequency band, waveform-generation approach, sweep or modulation bandwidth, communication metric, and sensing metric.

Table 4. Comparison of representative photonic THz ISAC demonstrations. The table compares frequency band, waveform-generation format, sweep or modulation bandwidth, communication throughput, and sensing resolution to clarify the trade-offs between communication and sensing performance.

Ref.	Frequency Band	Integrated Waveform	Modulation Bandwidth	Communication Metric	Sensing Metric
[141]	134 GHz	LFM + 16QAM	30 GHz	116 Gbit/s	6 mm
[142]	275 GHz	LFM + 16QAM	25 GHz/ch.	120 Gbit/s	25 mm
[143]	300 GHz	Dual-chirp LFM + QPSK	10 GHz	20 Gbit/s	15 mm
[144]	330 GHz	LFM-BPSK	18 GHz	6 Gbit/s	13 mm
[145]	340 GHz	LFM + PS-256QAM-OFDM	10 GHz	38.1 Gbit/s	15.8 mm
[146]	300 GHz	SFCW + LFM	40 GHz	2 Gbit/s	7.5 mm
[147]	240 GHz	FMCW + 2-FSK	7.9 GHz	2 Gbit/s	~10 mm

Abbreviations: ISAC: integrated sensing and communication; LFM: linear frequency modulation; SFCW: stepped-frequency continuous-wave; FMCW: frequency-modulated continuous-wave; QAM: quadrature amplitude modulation; BPSK: binary phase-shift keying; QPSK: quadrature phase-shift keying; FSK: frequency-shift keying; OFDM: orthogonal frequency-division multiplexing; PS: probabilistically shaped.

A more exploratory but potentially powerful direction is to exploit the intrinsic nonlinear dynamics of semiconductor lasers for fast frequency reconfiguration and waveform generation. In optically injected semiconductor lasers, period-one (P1) or period-two (P2) oscillations can generate microwave or millimeter-wave signals through nonlinear laser-cavity dynamics rather than through conventional electronic waveform synthesis. Recent studies have demonstrated P1-based microwave frequency switching and switching-delay regulation [167,168], externally locked frequency-modulated microwave generation based on perturbed P1 dynamics [169], tunable V- and W-band microwave generation using stabilized P1 dynamics [170], microwave generation based on P2 dynamics [171], and reconfigurable dual- or multichirp LFM waveform generation using optical injection in semiconductor lasers [172,173]. A broader overview of P1 laser dynamics for photonic microwave generation is given in [174]. These results suggest a promising route toward compact and agile photonic waveform sources for future THz ISAC systems. However, their practical use in UTC-PD-based THz transmitters will require improved control of switching delay, chirp linearity, phase noise, injection stability, and system-level compatibility with photomixing-based THz generation.

3.2. Array-Based Beam Manipulation

At THz frequencies, directional transmission is not merely advantageous but fundamentally required. The severe free-space propagation loss of the THz band, combined with the limited radiated power available from a single UTC-PD, makes high-gain emission essential for practical wireless links. In this context, beam manipulation in UTC-PD-based photonic THz transmitters can be understood along two related directions: coherent multi-element radiation using antenna-integrated UTC-PD arrays, and frequency-dependent beam control using dispersive radiating structures such as leaky-wave antennas, as illustrated in Figure 8.

Antenna-integrated UTC-PD arrays, shown schematically in Figure 8a, directly address the power and beam-control requirements by distributing optical excitation across multiple UTC-PD elements. These architectures enable coherent continuous [175–178] and pulsed [179–181] THz wave power enhancement while simultaneously introducing spatial control through optical-domain phase, delay, frequency, or amplitude tuning. Their importance therefore extends beyond simple power scaling, since the same transmitter architecture can also support beam shaping, steering, and multibeam operation. This array-based perspective has gradually shifted photonic THz transmitters from isolated radiating devices toward optically programmable radiating apertures.

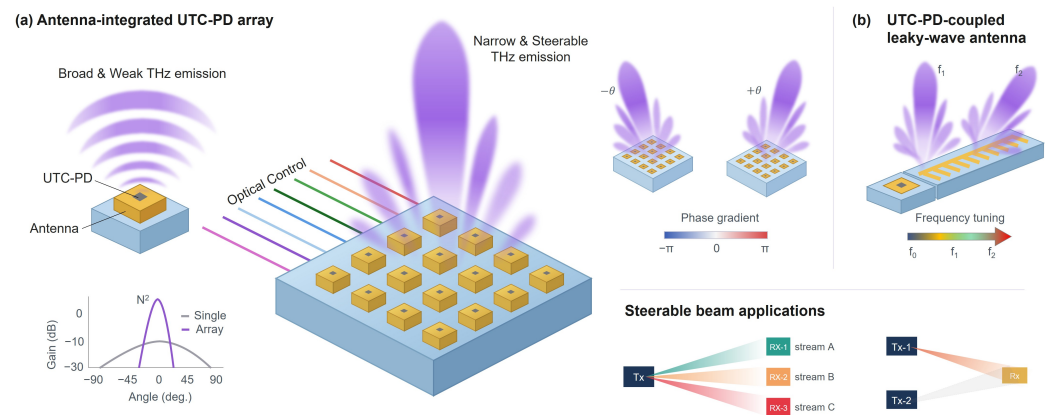


Figure 8. Array-based beam manipulation in UTC-PD-based photonic THz transmitters. Antenna-integrated UTC-PD arrays enable coherent power combining and optical-domain control of the radiated field through element-level phase, delay, frequency, or amplitude tuning, while dispersive radiating structures such as leaky-wave antennas provide frequency-dependent beam steering.

It should also be noted that a related line of development has pursued power enhancement without introducing spatial tunability. In these architectures, the outputs of multiple UTC-PDs are combined through planar or waveguide power-combining circuit networks, including planar T-junction [182–186], planar Wilkinson-type [187,188], and Y-junction waveguide combiners [189,190]. Although these approaches do not provide beam control capability directly, they remain highly important from an engineering perspective because they support source modularization, improve coupling efficiency to antenna or waveguide interfaces, and provide a practical route toward compact high-power THz transmitter modules.

In contrast to multi-element UTC-PD arrays, leaky-wave antennas and other dispersive radiating structures, as shown in Figure 8b, provide a simpler route to beam steering by exploiting frequency-dependent radiation. In this case, the beam direction is controlled through the carrier frequency rather than through element-by-element phase control. This approach reduces the need for distributed optical routing and phase-control circuitry, but it also intrinsically couples beam direction to carrier frequency. Therefore, array-based and dispersion-based beam-control architectures offer different trade-offs between steering flexibility, hardware complexity, aperture scalability, and frequency independence.

This comparison clarifies why different beam-manipulation architectures should be evaluated using multiple criteria rather than by steering range alone. Antenna-integrated UTC-PD arrays and optoelectronic phased arrays provide element-level control of the radiated field and can, in principle, decouple beam direction from carrier frequency. Their limitation is the scaling of optical routing, phase-control circuitry, chip area, and thermal management with the number of elements. Leaky-wave antennas and other dispersive radiators provide simpler hardware and continuous frequency-controlled scanning, but beam direction is intrinsically coupled to carrier frequency. Therefore, future beam-manipulation architectures should be evaluated not only by steering range but also by aperture scalability, beam-control latency, frequency independence, link robustness, and packaging feasibility.

Table 5 summarizes these trade-offs for representative UTC-PD-based beam-steering architectures. These criteria are consistent with recent THz beam-steering reviews, which compare beam-control technologies in terms of steering angle, bandwidth, radiation efficiency, aperture scalability, compactness, and implementation complexity [191,192]. Complementary aperture-side approaches, including reconfigurable intelligent surfaces, programmable metasurfaces, and tunable THz metalenses, may further support coverage extension, blockage mitigation, and adaptive beam-power control [193–199]; however,

these approaches are not UTC-PD-specific transmitter architectures and are therefore outside the main scope of this review.

Table 5. Qualitative comparison of UTC-PD-based THz beam-steering architectures. The table summarizes the main trade-offs between antenna-integrated UTC-PD arrays and UTC-PD-coupled leaky-wave antennas in terms of complexity, radiation efficiency, bandwidth and frequency dependence, aperture scalability, compactness, tunability, versatility, and feed type.

	Antenna-Integrated UTC-PD Array	UTC-PD-Coupled Leaky-Wave Antenna
Complexity	High	Moderate
Radiation efficiency	High but phase-sensitive	Moderate
Bandwidth	High; frequency-independent	Lower; frequency-coupled
Aperture	Large; footprint-limited	Compact; scalable
Compactness	Moderate-to-low	High
Tunability	High	Moderate
Versatility	High	Moderate-to-high
Feed type	Distributed	Single

3.2.1. Antenna-Integrated UTC-PD Array

Beam control in photonic THz transmitters fundamentally originates from the excitation distribution established across adjacent radiating elements. In this respect, antenna-integrated UTC-PD arrays differ substantially from conventional phased-array antennas. Because each antenna element is co-integrated with an active UTC-PD, the primary beam-control variables are transferred from the THz domain to the optical domain, including optical phase, delay, frequency, and amplitude. This shift is particularly attractive because optical-domain control of these quantities is significantly more mature and experimentally accessible than their THz-domain counterparts.

Based on this principle, several optoelectronic beamforming networks have been explored, including fiber-delay distribution networks [200–203], optically controlled phased arrays [204–208], and dispersion-engineered feeding structures [209,210]. Representative demonstrations in the 300 GHz band have confirmed the feasibility of beam steering from one-dimensional (1D) to two-dimensional (2D) configurations using these approaches [211]. Under ideal coherent excitation with fixed per-element power, the peak directional intensity can scale as N^2 relative to that of a single antenna-integrated UTC-PD, where N denotes the number of radiating elements.

Beyond static beam formation, recent work on UTC-PD-based optoelectronic phased arrays has shifted the role of beam control toward adaptive and communication-oriented spatial management. Feedback-based optical phase control, incorporating hill-climbing [212] and genetic algorithms [213], has achieved automatic THz beam steering in an arrayed UTC-PD chip. This concept was subsequently extended to beam-steering wireless data transmission using arrayed UTC-PDs on a high-thermal-conductivity SiC substrate, where the communication quality was shown to be primarily governed by the received THz intensity [214–216]. In parallel, recent studies have addressed the frequency dependence and stability limitations of photonic phased arrays. Optical phase compensation stabilized the beam during carrier switching from 290 to 305 GHz and improved beam stability by 1.29 dB [217], while feed-forward phase pre-compensation further enabled frequency-independent beam steering during both frequency hopping and frequency sweeping operations [218]. Real-time received-power feedback has also been introduced for dynamic beam tracking, achieving a static synthesis gain of 11.5 dB and tracking a moving receiver over $\pm 40^\circ$ at angular velocities up to 3.58 deg/s [219]. In this sense, future progress will be determined less by larger steering angles or faster scanning speeds alone and more by how effectively beam controllability can be translated into stable, adaptive, and communication-oriented system operation.

Despite this potential, practical scaling remains challenging. The physical footprint of the radiating aperture is substantially larger than that of the UTC-PD itself, so increasing the number of array elements rapidly increases chip area, optical routing complexity, and monolithic integration cost. Moreover, the ideal N^2 scaling of peak radiated intensity is achievable only under coherent excitation with well-controlled phase and amplitude matching, whereas routing loss, phase error, thermal crosstalk, and element nonuniformity generally become more severe as N increases. Consequently, most reported UTC-PD arrays still employ only a limited number of radiating elements, resulting in relatively broad beamwidths, limited steering range, and limited angular resolution. Therefore, the realizable aperture size, rather than the demonstration of optoelectronic steering itself, is emerging as a major practical limitation for UTC-PD-based beamforming architectures. Future progress will require larger, more efficiently coupled, and more manufacturable radiating apertures for high-capacity THz wireless systems.

3.2.2. UTC-PD-Coupled Leaky-Wave Antennas

In contrast to array-based approaches that impose an excitation distribution directly across the radiating aperture, another class of beam-steering architectures exploits dispersive radiators to translate the frequency agility of a photonic THz source into beam-direction control. Representative examples include transmitters employing leaky-wave antennas (LWAs), in which the main-beam angle varies continuously with operating frequency. In such systems, beam scanning can therefore be realized by tuning the THz carrier generated through optical heterodyning.

The main advantage of this approach lies in its structural simplicity. Because beam steering is achieved through frequency tuning rather than distributed phase or delay control, the architecture avoids the complexity of fully distributed beamforming networks while still benefiting from the maturity and continuity of optical frequency control. Recent demonstrations have shown that such schemes can support not only 1D beam steering but also more flexible communication functions including mobile-link tracking, multi-user access, and point-to-multipoint transmission.

This simplicity, however, comes with an inherent constraint. Since beam direction is coupled to carrier frequency, the achievable angular coverage, steering resolution, and communication bandwidth cannot be optimized independently. The main challenge is therefore no longer to demonstrate frequency-controlled beam deflection but to establish a practical balance among frequency agility, angular coverage, spectral allocation, and communication-link requirements.

The development of LWA-based photonic THz transmitters reflects this transition from proof-of-principle demonstration toward communication-oriented spatial control. Early demonstrations at E-band employed periodically loaded microstrip LWAs and established the basic principle of frequency-controlled beam steering, achieving approximately 22° beam scanning and 2.15 Gbit/s wireless transmission around 80 GHz [220]. As research moved toward the 300 GHz band, InP-based LWAs became increasingly attractive because of their compatibility with UTC-PDs and photonic integration [221,222]. These structures expanded the steering range to nearly 90° across the WR-3 band while maintaining a relatively constant antenna gain. More recently, SiC-based dispersive radiating structures have been further extended toward the 600 GHz band [223].

In parallel, dispersive radiators have evolved from simple periodic microstrip structures to planar Goubau-line LWAs [224] and LWA arrays combined with beamforming networks, enabling not only 1D frequency scanning but also 2D steering with measured angular coverage of 92° in elevation and 39° in azimuth [225]. More importantly, the focus has gradually shifted from antenna characterization to communication-oriented demon-

strations. Frequency-steerable photonic transmitters have supported mobile THz links with data rates up to 24 Gbit/s [226], while recent point-to-multipoint systems achieved 35 Gbit/s over 30 cm, 5 Gbit/s over 1.1 m, and simultaneous multi-user transmission with independent 10 Gbit/s and 5 Gbit/s channels [227]. These results collectively indicate that LWAs are evolving from frequency-scanned radiators into communication-oriented spatial interfaces, where optical frequency programmability, beam control, and multi-user wireless functionality are integrated within a common photonic THz transmitter architecture.

Taken together, these demonstrations show that photonic THz beam steering has evolved from basic frequency- or phase-controlled beam deflection toward more quantitative evaluations of angular coverage, dimensionality, aperture size, and gain. To provide a clearer comparison across different implementations, Table 6 summarizes representative photonic THz beam-steering demonstrations and their key performance metrics.

Table 6. Quantitative comparison of representative photonic THz beam-steering demonstrations. The table summarizes carrier frequency, UTC-PD count, antenna type or array configuration, steering dimensionality, steering range, and reported broadside gain to compare beam-control performance across different implementations.

Ref.	Frequency Band	UTC-PD Count	Antenna	Steering	Steering Range	Gain
[204]	300 GHz	4	4 × 4 slot	1D	50°	N.G.
[208]	300 GHz	4	1 × 4 bowtie with silicon lens	1D	20°	10.6 dB
[211]	300 GHz	4	2 × 2 MPA	2D	360° (az.); 25° (el.)	9.67 dB
[219]	300 GHz	4	1 × 4 MPA	1D	±40°	11.5 dB
[220]	75–85 GHz	2	2 LWAs	1D	22°	18 dBi
[221]	230–330 GHz	1	1 LWA	1D	88°	11 dBi
[225]	230–330 GHz	3	3 LWAs	2D	39° (az.); 92° (el.)	13.7 dBi
[226]	280–330 GHz	1	1 LWA with Teflon lens	1D	33°	23 dBi
[227]	230–330 GHz	1	1 LWA	1D	90°	14 dBi

Abbreviations: MPA: microstrip patch antenna; LWA: leaky-wave antenna; az.: azimuth; el.: elevation; N.G.: not given.

4. Outlook

As summarized in Figure 9, near-term progress toward deployable photonic THz wireless systems depends first on resolving several coupled physical-layer and implementation constraints. The limited output power of UTC-PD-based emitters remains a central link-budget limitation, particularly above 300 GHz [228,229]. Although increasing the photocurrent can raise the emitted power, it also introduces thermal-management and reliability concerns [214,216]. Compact packaging must simultaneously provide low-loss optical coupling, efficient THz radiation or waveguide coupling, and stable mechanical alignment [12,189]. On the receiver side, sensitivity, bandwidth, linearity, and power consumption determine whether high-order modulation and long-distance transmission can be sustained outside laboratory conditions. Moreover, because many high-capacity demonstrations still rely on offline digital signal processing (DSP), practical systems will require low-latency real-time equalization, synchronization, and beam management. These constraints call for coordinated source–emitter–antenna–receiver–DSP design rather than separate optimization of individual components.

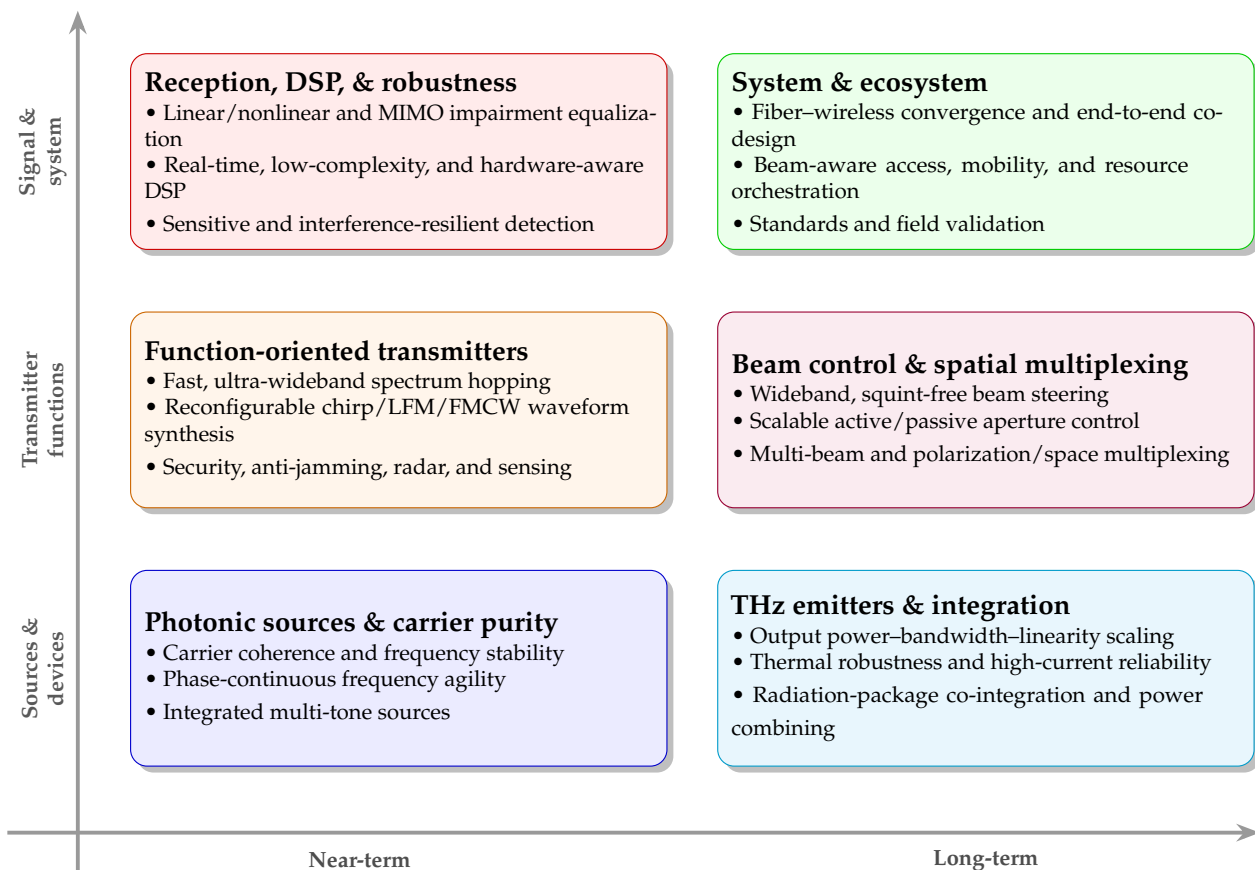


Figure 9. Roadmap for UTC-PD-enabled photonic THz wireless communications toward 6G and beyond. The vertical dimension groups challenges from photonic sources and devices to transmitter functions and system-level operation, while the horizontal direction indicates near-, mid-, and long-term progression. Each box lists representative open research problems, and supporting references are grouped as follows: Photonic sources & carrier purity [98,100–112,133–135,148,156,167]; THz emitters & integration [12–15,43,52,175,189,214,216,223,228,229]; Function-oriented transmitters [123,125,127–137,143,146,147,154,215,230,231]; Beam control & spatial multiplexing [46,47,113,116,118,193,194,197,198,204,208,210,211,217–219,221,225,227]; Reception, DSP, & robustness [37,40,42,44,47,48,53,55,60,90,92,93,119,120,127,129,138,232]; and System & ecosystem [12,21,40,41,49,51,52,78,233–242].

These device- and packaging-level requirements are consistent with broader efforts toward integrated electronic, photonic, and hybrid THz systems, in which antenna integration, power efficiency, thermal robustness, receiver performance, and real-time signal processing must be considered jointly. Building on such integrated front ends, future systems can combine programmable waveform generation and beam control with integrated sensing and communication (ISAC), artificial-intelligence (AI)-assisted control, and security-aware operation. The narrow beams, large bandwidths, and propagation sensitivity of THz links make sensing-assisted alignment, environmental awareness, adaptive control, and resilient transmission particularly valuable [230,231,242–248]. Mobility-oriented scenarios, including vehicular links and smart-rail systems, provide important test cases because they simultaneously require high-capacity transmission, accurate beam management, and robust channel adaptation under dynamic propagation conditions [232,236,237,240].

Beyond the physical-layer front end, deployable THz networks will require reliable link establishment, medium access control (MAC), beam-aware resource allocation, standardized channel models, and interoperability with emerging THz channel plans [233–235,239,241]. These cross-layer capabilities are necessary to translate the wave-

form and beam-control functions discussed in this review into stable multi-user and mobile network operation.

From a standardization and commercialization perspective, alignment with existing and emerging THz channelization frameworks, including IEEE 802.15.3d-compatible operation [51,238,239], will be important for interoperability and meaningful system comparison. Industrial adoption will depend less on further record values alone than on manufacturable and packaged UTC-PD modules, stable optical and THz coupling, low-power real-time DSP, compatible channel plans, and reproducible field performance. Bridging laboratory demonstrations and standards-compliant, field-operable systems therefore remains the central long-term challenge.

5. Conclusions

This review revisited the progress of UTC-PD-enabled photonic THz wireless communications from the perspective of faster-and-farther point-to-point demonstrations and their subsequent functional expansion. Over the past two decades, photonic THz links have evolved from feasibility-oriented experiments into ultra-high-capacity wireless systems, with representative demonstrations reaching higher single-channel rates, larger aggregate capacities, and longer transmission distances. This progress has established UTC-PD-based photonic transmitters as a viable platform for high-frequency wireless transmission, owing to their wide carrier tunability, modulation transparency, and compatibility with optical communication technologies.

This review also shows that recent performance records cannot be attributed to UTC-PD improvement alone. Rather, they have resulted from the coordinated development of low-noise optical sources, multiplexing architectures, and receiver-side equalization. Low-noise source engineering improves the spectral purity and stability of the generated THz carrier; multiplexing converts the available THz bandwidth into multiple usable transmission dimensions; and equalization enables reliable recovery under bandwidth limitation, channel distortion, polarization coupling, and device nonlinearity. In this sense, high-performance photonic THz wireless links are best understood as integrated source–transmission–reception systems rather than isolated transmitter demonstrations.

At the same time, the field is gradually moving beyond fixed point-to-point links. The same optical-domain controllability that supports high-capacity transmission is now being used to introduce new transmitter-level functions. Laser-frequency programmability enables waveform-defined operation, including photonic THz frequency hopping and integrated sensing and communication. Antenna-integrated UTC-PD arrays and dispersive radiating structures further extend photonic THz transmitters toward beam steering, beam switching, and spatially reconfigurable links. These directions do not replace the faster-and-farther trajectory but extend it toward more programmable and communication-oriented transmitter architectures.

Despite the rapid progress summarized in this review, several bottlenecks still limit practical deployment. UTC-PD transmitters must further improve emitted THz power and robustness while maintaining low phase noise and broad tunability. Receiver sensitivity, compact packaging, optical alignment, and antenna integration remain critical for field operation. At the system level, advanced DSP and equalization must move from offline processing toward low-latency real-time implementation. Future research should therefore focus on co-designing photonic sources, UTC-PD emitters, radiating apertures, receivers, and signal processing as an integrated link architecture rather than optimizing individual components in isolation.

Taken together, the central challenge is shifting from demonstrating whether UTC-PD-based photonic THz links can reach extreme data-rate or distance records to determining

whether such performance can be reproduced in architectures that are stable, scalable, functionally flexible, and suitable for practical deployment. This shift defines the broader transition from faster-and-farther link demonstrations toward deployable and function-oriented photonic THz wireless systems.

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