Beyond 100 Gb/s Optoelectronic Terahertz Communications: Key Technologies and Directions

Lu Zhang, Xiaodan Pang, Shi Jia, Shiwei Wang, and Xianbin Yu

The authors present technical insight into the key technologies of optoelectronic terahertz communications with high data rates in the physical layer, including approaches of broadband devices, baseband signal processing technologies, and design of advanced transmission system architectures.

Abstract

The terahertz band (0.1 THz–10 THz) with massive spectrum resources is recognized as a promising candidate for future rate-greedy applications, such as 6G communications. Optoelectronic terahertz communications are beneficial for realizing 100 Gb/s data rate and beyond, which have greatly promoted the progress of the 6G research. In this article, we give technical insight into the key technologies of optoelectronic terahertz communications with high data rates in the physical layer, including approaches of broadband devices, baseband signal processing technologies, and design of advanced transmission system architectures. A multicarrier signal processing routine with high noise tolerance is proposed and experimentally verified in a 500 Gb/s net rate terahertz communication system. Finally, we discuss the future directions of optoelectronic terahertz technologies toward the target of terabit-scale communications.

Introduction

Recently, the remarkable explosion of wireless devices and bandwidth-consuming Internet applications have boosted the demand for ultra-high data rate wireless communications. According to the latest Cisco visual networking index report [1], 5G connection will generate three times more traffic than 4G connections by 2023. Furthermore, wireless traffic volume is foreseen to be sufficient to match or even surpass the wired services by 2030, and the high precision wireless services will need to be guaranteed with a peak data rate of well beyond 100 Gb/s, eventually 1 Tb/s [1]. To meet the exponentially increasing traffic demand, new regions in the radio spectrum are explored. The terahertz band (0.1–10 THz) [1], sandwiched between microwave frequencies and optical frequencies, is considered as the next breakthrough point to revolutionize the communication technology attributed to its rich spectrum resources. In 2008, IEEE 802.15 established the THz Interest Group, and IEEE Std.802.15.3d-2017 was issued in 2017 as the first wireless communication standard in the 300 GHz band [1]. In the World Radiocommunication Conferences 2019, the identification of frequency bands in the frequency range 275–450 GHz is permitted for the use of land-mobile and fixed services applications, indicating potential standardization of the low frequency window of the terahertz band for near-future wireless communications.

The terahertz communication technologies can be clustered as pure electronic schemes and optoelectronic schemes [2]. In terms of supporting high data rates, the photonic heterodyne-based optoelectronic scheme is currently analyzed by many research teams [3–9] because of its large bandwidth and small harmonic interference advanced by optoelectronics. Such a scheme also maintains the benefits of radio frequency (RF) communications, such as flexible user access, ease of deployment at a relatively lower cost, and the long-term accumulated technological experience and momentum in many wireless applications. Furthermore, this scheme facilitates its seamless convergence with high-speed fiber access networks. Thus, the optoelectronic terahertz communication inherits the advantages of both RF and fiber optic communications, forming a bridge between the wireless and wired networks.

In Fig. 1 we summarize some state-of-the-art reports, to the best our knowledge, on experimental terahertz demonstrations [2-9]. This summary is to show a general picture of the research frontline and is by no means all-inclusive. The electronic and optoelectronic methods for terahertz communications are promoting each other in emerging to a more established field. Terahertz communications arose around 2000 upon the initiation of a 120 GHz wireless link enabled by photonic technologies [2], and the achievements have triggered the progress of electronic devices to further strengthen wireless technology.

The electronic terahertz communication systems are mainly realized by complementary metal oxide semiconductor (CMOS)-based transceivers or monolithic microwave integrated circuits (MMICs). In CMOS technology, the frequency is multiplied from a lower band to the terahertz frequency band by using nanoscale CMOS circuits, and it possesses the advantages of high-level integration, small form factor, and potential low cost. In 2017, up to 105 Gb/s data rate was achieved using a 40 nm CMOS process at 300 GHz [1].

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The MMIC technology is basically implemented by assimilating many high-speed transistors into a small chip and makes higher frequency sources with higher output powers possible. However, the electronic methods are facing challenges, such as difficulties in further scaling up the modulation bandwidth and depth, and the nonlinear harmonics from the multiplier chain, which may impose limitations in adopting it for the development of terahertz communications.

The optoelectronic terahertz communication systems can be realized by a photonic heterodyne scheme with a uni-traveling wave photodiode (UTC-PD) or a direct modulation scheme with a quantum cascade laser (QCL). While QCLs normally generate signals at the high-frequency terahertz window, the UTC-PD is more suitable for wireless communications at the sub-terahertz window. Compared to solid-state electronics, optoelectronic technologies feature benefits such as large bandwidth, high modulation index, and less harmonics, and it can easily realize multi-carrier transmission by allocating multiple optical tones to the UTC-PD-based photo-mixer. Besides, dimensions in the optical domain, wavelength, polarization, complex amplitude, and other domains can be multiplexed to realize record high-speed terahertz communications, such as polarization multiplexing-based 1 Tb/s transmission at D-band [5] and wavelength-division-multiplexing-based 260 Gb/s transmission at 300–500 GHz [7]. These demonstrations with optoelectronic schemes to date in general show an edge over the electronic counterpart in terms of achievable data rates. One should note that most of these optoelectronic schemes employ pure electronic receivers, such as a harmonic mixer using GaAs Schottky barrier diodes. Therefore, coexistence and complementary functions of the electronics and optoelectronics for developing terahertz communications can be expected in the foreseeable future.

Now, there is still a large gap to the target of 1 Tb/s in 6G, and the following aspects need to be further improved in terahertz communications:

- Devices: The reported optoelectronic terahertz transmission systems are mainly based on bulky discrete components. Development of chip-based compact devices is required to improve the compactness.
- Signal processing: The importance of the baseband signal processing design is underestimated at the early stage of terahertz communications; a broadband signal processing methodology that fits the properties of terahertz band is a key to boost the data rates.
- Systems: Advanced system design gaining from multiplexing techniques in the optical domain is of great importance to overcome the single-channel physical limits and to realize high-speed terahertz communications.

In this article, we recognize the application scenarios of high-speed terahertz communications and focus on the key technologies enabling beyond 100 Gb/s optoelectronic terahertz communications, including progress on the devices, the signal processing, and the systems. We show the technological potential of this approach by presenting a system demonstration of 500 Gb/s net rate transmission with an advanced signal processing routine. Finally, we extend our discussions onto the future technological trends toward 1 Tb/s wireless communications.

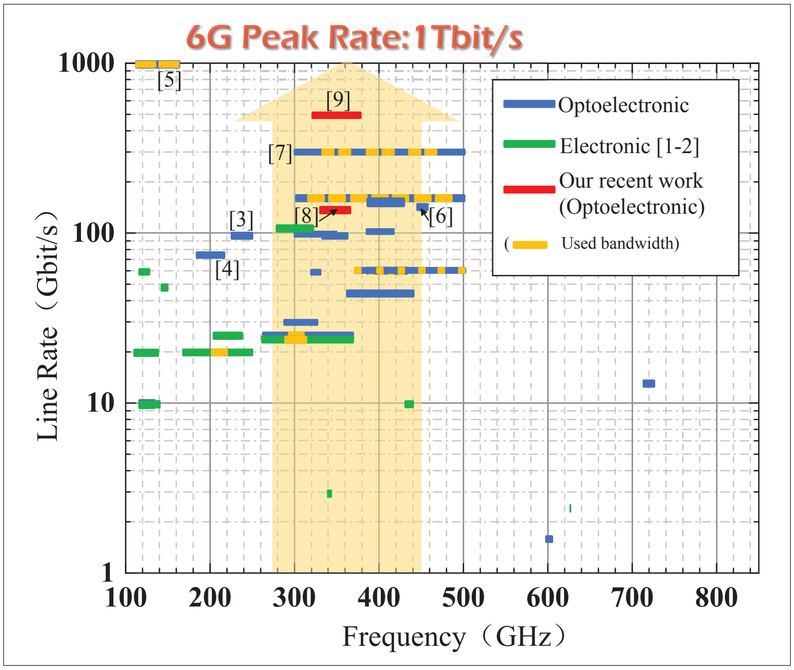

Figure 1. State-of-the-art reports on the experimental demonstrations of terahertz communications.

Application Scenarios

Transmission technologies and applications in telecom and datacom are always coupled together and driving each other forward. High transmission data rates will catalyze the emergence of more rate-greedy applications, and the development of such applications will also generate more traffic and motivate higher network capacity. 6G can be recognized as an information ecosystem, in which numbers of applications can be enabled by ultra-high-speed terahertz connectivity. In this article, we preliminarily categorize these application scenarios into nanoscale and macroscale, as shown in Fig. 2.

Nanoscale Applications

Nanoscale applications are mainly in the field of biomedical, healthcare, environment monitoring, and the Internet of Nano-Things, among others. The nanoscale components are in centimeters, and each nano-chip is responsible for a specific task, like video monitoring, data storage, and specific computation [1]. A terahertz link with over 100 Gb/s data rate is a potential block to interconnect the nanoscale components, building a high-capacity local area network to perform specific tasks. Note that the link distance of nanoscale applications is very short, typically in the range from several millimeters to a few meters, so the path loss of these links is small, and hence the requirement on the terahertz source power is relaxed.

Macroscale Applications

For macroscale applications, the range of terahertz communication links can span from tens of meters to the order of kilometers [2], such as wireless access networks and data center networks [1, 15].

Optoelectronic terahertz communications can utilize the fibers to remotely feed the broadband THz emission frontends in backhaul networks. The terahertz access network could also be used for some other typical applications, such as outdoor inter-vehicular communications and indoor kiosk downloading.

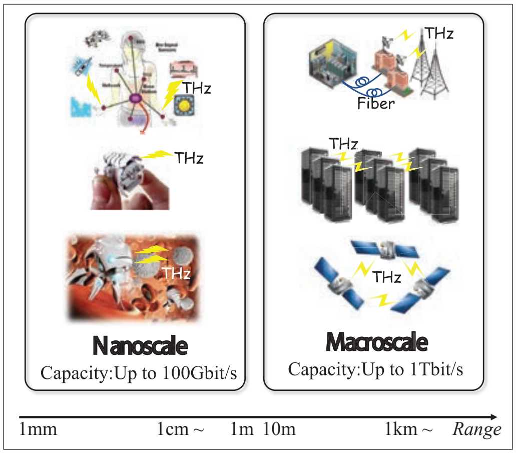

Figure 2. Terahertz communication application scenarios.

With the progress of cloud radio access networks (C-RAN), the fronthaul data rate is increasing dramatically due to the digitized transmission protocol of C-RAN. The optoelectronic terahertz communications could be utilized as a novel fronthaul scheme to extend the reach of fronthaul coverage range, and high-capacity-demanding users can be offloaded to the terahertz band by adjusting the optical carriers at the central office; the spectrum at lower frequency band is released to the other users without scarifying the existing fiber-based access infrastructure [1, 15]. Moreover, strong backhaul network support is crucial for high-speed wireless access. The optoelectronic terahertz communications could also be used to support the backhaul network by building THz-fiber-THz bridges and fiber-THz-fiber bridges. Furthermore, optoelectronic terahertz communications can utilize the fibers to remotely feed the broadband THz emission frontends in backhaul networks. The terahertz access network could also be used for some other typical applications, such as outdoor inter-vehicular communications and indoor kiosk downloading.

The data center network is another potential application scenario for terahertz communications. With the development of cloud applications and the increasing support of mobile services, the required interconnection speed among servers in data centers is increasing. The introduction of optical-fiber-based short reach links has decreased the cabling complexity of the data center, and the power consumption has been reduced. The optical-fiber-based 400 Gb/s Ethernet is being deployed, and an 800 Gb/s Ethernet product has been issued [1]. Compared to electronic terahertz communications, optoelectronic terahertz communications could provide the aforementioned "fiber-like" transmission speed with enhanced free space transmission with mobility; it can therefore enable rack-scale free space direct connection and enhance the scalability of data center networks.

Full space coverage is an important indicator of 6G. The atmospheric attenuation of the terahertz band in the space environment is almost negligible, and the free space path loss needs to be compensated for by very high-gain antennas or antenna arrays. Compared to the microwave/millimeter/terahertz electronic systems, optoelectronic terahertz communications can accommodate larger capacity, which is crucial for providing high-capacity links to remote areas. However, in the satellite network, the distance is longer and beam alignment is more difficult, so the terahertz power needs to be enhanced. Thus, the electronic terahertz systems are more useful in terms of signal power. The integration of photo-mixer, terahertz power amplifier, and high-gain antenna could be a promising direction for satellite communications.

Therefore, high-speed optoelectronic terahertz communication is an important chess piece that could enliven the situation of future communication applications.

Optoelectronic Terahertz Devices

In the early decade of terahertz research, laser-inspired devices are commonly used for generating ultra-high terahertz waves, such as femtosecond lasers, to cope with photoconductive antennas or nonlinear optical crystals [10]. However, their tabletop/benchtop size, unstable performance, and/or high power consumption are not suitable for real-world wireless applications. Nowadays, terahertz devices are being developed in the integrated and chip-scale directions, and optoelectronic THz devices with footprints less than 1 mm^2 have been reported [14]. The optoelectronic terahertz generation schemes and devices [10] are mainly categorized into three parts:

1. A photo-mixer-based heterodyne scheme for generating up to milliwatt power level terahertz signals in the low frequency window below 1 THz
2. Terahertz QCL for generating microwatt to milliwatt power level terahertz signals
3. An optical nonlinear materials-based scheme for parametrically generating milliwatt power level terahertz signals in the high frequency window well beyond 1 THz

There is no point in discussing which one is more advantageous, since typical applications will require different frequency ranges, power levels, and system bandwidth. For wireless communications, the photo-mixer method, which is shown in Fig. 3, is studied because of its compatibility with existing fiber optic networks and its high compactness, due to the development of photonics integrated circuits.

In Fig. 3, two optical carriers are used to drive the photo-mixer, with one of frequency f1 used as the optical local oscillator (LO) and another of frequency f2 driving the optical modulator. The quality of the THz signal is directly related to the optical carriers illuminating the photo-mixer. Phase-correlated optical carriers with narrow line width could ensure a low-phase-noise THz carrier, and several methods have been proposed to target this goal [2], such as optical broadband comb with phase stabilization, multi-mode laser with a single cavity, and injection locking of integrated lasers. After the optical carrier generation, the broadband signal is modulated to the optical domain by optical modulators. It is worth noticing that the signal locates as the optical baseband, which can make use of the rich bandwidth of modulators, such as the Mach-Zehnder modulator (MZM). An MZM with low half-wave voltage could provide high modulation index. Subsequently, the optical LO and optical baseband modulation signal are coupled into one branch and boosted by an optical power amplifier. The terahertz signal is generated by photo-mixer-based heterodyne detection, and the signal on f2 is down-converted to f1 – f2 = f THz. The UTC-PD is used as the photo-mixer here, which supports only electrons as active carriers traveling through the device, providing benefits like high operation speed, large output saturation current, and low operation voltage. However, the UTC-PD is a polarization-sensitive device, so an optical polarization controller is therefore needed before the UTC-PD to optimize the conversion efficiency. To tackle the beamforming issue of terahertz signals, an optical true time delay network along with a photo-mixer array could be a feasible solution to flexibly control terahertz beams.

The receiver can be either electronic (e.g., a Schottky-barrier diode) or optical (e.g., a broadband plasmonic modulator [14]) to pick up the incoming terahertz signals.

The traditional radio transceivers are based on solid-state electronics, such as CMOS and MMIC technologies. The modulation is commonly realized by a multiplier chain from a lower band to the terahertz frequency band, or direct modulation by changing the amplitude or phase of propagated terahertz waves. Compared to the scheme in Fig. 3, traditional radio-transceiver-based terahertz communication is influenced by the limited modulation bandwidth and index, and the phase noise and nonlinear harmonics cause more severe degradations. However, traditional radio transmitters normally provide higher transmitting signal power.

Most high-speed optoelectronic terahertz communication experimental demonstrations are still testified using III-V (e.g. InP) semiconductor devices in the lab, and each device is separately developed to optimize the performance. Recently, there has been some research work on monolithic and hybrid-substrate integrated photonic circuits for terahertz communications. Reference [11] reports a fully monolithic chip with two lasers, optical amplifiers, an optical intensity modulator, and photodiodes, fabricated on the InP substrate. Reference [12] reports a hybrid-substrate InP-polymer dual tunable laser chip for generating terahertz wave up to 4 THz. To achieve high programmability and flexibility, the hybrid-substrate integration scheme is optimized more easily than the monolithic scheme. The monolithic scheme features a high integration level, but at a higher cost than the hybrid scheme.

Future Directions

The development of optoelectronic terahertz devices will greatly influence the pace to bridge the technology and application gap of the terahertz communications. The transmitting power, energy consumption, and chip size are among the key aspects to attract effort in development for the near future.

Photonics integration technology is progressing rapidly, which could push optoelectronic terahertz communication toward the terabit-on-chip target. Photonics integration is a feasible approach to improve transmitting power and reduce energy consumption. First, the connection loss, such as the loss between fiber tap and chip, can be largely reduced. Second, the energy consumption for temperature control of a single chip can be lower than separated components. To further improve the transmitting power, integrated multiple photo-mixers with output power combining technology is a promising approach.

The progress of Si photonics integration technology paves a new way for development of optoelectronic terahertz communications. Higher than –15 dBm transmitting power at 180 GHz has been realized with a Ge-based photo-mixer in a Si platform [2]. The Si photonics integration technology also makes its integration with Si electronics and low-loss waveguides easier, which is expected to further improve the system efficiency. New materials are also interesting directions for terahertz technologies. For instance, graphene-based technology is an encouraging direction, where graphene metamaterials could be used for modulators, and graphene field-effect transistors could be used for detection.

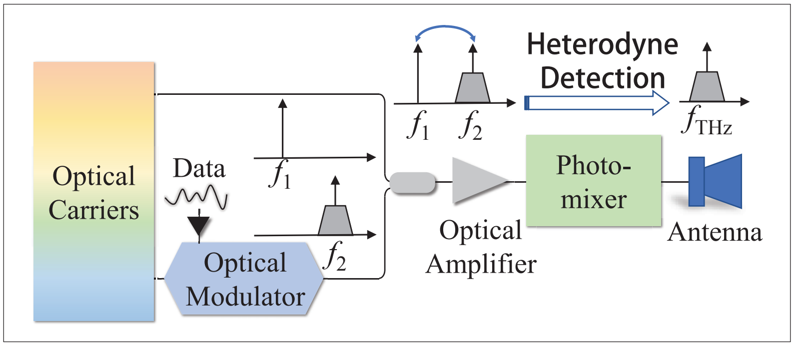

Figure 3. Photo-mixer-based terahertz signal generation scheme.

Baseband Signal Processing

Compared to its sister millimeter-wave band, the terahertz band provides more available bandwidth for utilization. It is worth mentioning that the following properties of terahertz waves [13] also bring new challenges to baseband signal processing.

Looking into the frequency domain, terahertz communications exhibit stronger frequency-selective channel response [13], which is in part due to the absorption effect of terahertz waves. As a result, the single carrier signal processing scheme is sensitive to the un-flat channel response, and the system signal-to-noise ratio (SNR) is directly cut down due to the "buckets effect."

Looking into the time domain, the channel coherence time of terahertz waves is very short [13], resulting in rapid channel fluctuation and stronger Doppler spreading than the millimeter-wave band. The directive beam of terahertz waves has increased its sensitivity to the multipath interference, and the precise modeling of terahertz channel becomes difficult and time-consuming.

A multicarrier signal processing routine with high noise tolerance is presented for optoelectronic terahertz communications.

Constellation Design

High-order constellation design is a natural choice to enhance the system spectral efficiency. However, the noise tolerance dramatically decreases with the increasing constellation order. Since the

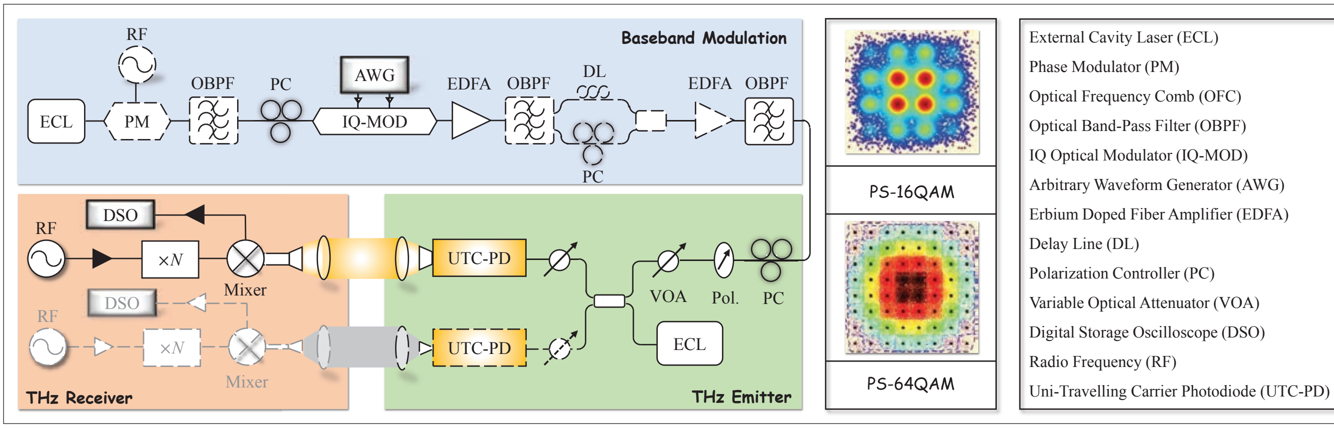

Figure 4. The multi-dimensional optoelectronic terahertz communication system. Insets: the recovered PS-16-QAM and PS-64-QAM constellations at the receiver side. (In the proof-of-concept experiment, only one terahertz receiver is used to successively receive the terahertz signals from both paths).

phase noise directly affects the constellation signal quality, the outer rings of a quadrature amplitude modulation (QAM) constellation are more sensitive to the system impairments.

The constellation shaping [8, 9] is realized by adjusting the constellation distribution probabilities with probabilistic shaping (PS) or adjusting the constellation Euclidean distances with geometric shaping. The most common scheme for realizing the probabilistic shaping is using the Maxwell-Boltzmann distribution principle [9]. The constellation points with lower energy (i.e., inner ring) are transmitted with higher probability than the constellation points with higher energy (i.e., outer ring). As a result, the PS-QAM constellation has improved noise tolerance and good bit-energy efficiency in the terahertz channel, where the radiation power is limited.

However, the shaping methods are mostly based on the additive white Gaussian channel noise assumption and the linear channel response. To suit the terahertz channel properties, adaptive training of the constellation distribution is required. A machine-learning-based training algorithm is an interesting direction to intelligently allocate the probabilities or distances; deep learning and auto-encoder are directions with consideration.

Modulation Waveform

The multicarrier signal processing routine [8,9] is analyzed to adapt the un-flat channel response of a terahertz channel. Multicarrier modulation, such as orthogonal frequency-division multiplexing (OFDM), divides the broadband into subcarriers. The constellation information at each subcarrier is flexibly adjusted, such as the constellation shaping arrangement and power allocation, to improve the entropy of the whole system. At frequency regions with high SNR, higher spectral efficiency constellation mapping is allocated.

To combat the double-dispersive channel response of the terahertz channel, some modifications of the OFDM scheme are open to discussion. To alleviate the inter-carrier interference, filtered OFDM schemes, such as filtered-OFDM and filter-bank multicarrier, could suppress the out-of-band side-lobes, and the frequency guard band could be saved. Orthogonal time-frequency-space modulation is another perspective to improve the noise tolerance. By mapping the signal to the delay-Doppler domain, each symbol is fully spread in the time-frequency domain, and the channel distortions exhibit similar influence on each symbol.

To improve the spectral efficiency, faster-than-Nyquist (FTN) techniques are promising for terabit-level terahertz communications. Apart from the fractional Fourier-transform-based spectrally efficient frequency-division multiplexing modulation waveform, overlapped X domain multiplexing modulation that transmits information with shifting and weighted transmission symbols in the time or frequency domain is another interesting technique to realize FTN spectral efficiency.

Channel Equalization

The broadband optoelectronic devices not only provide large bandwidth resource to the terahertz communication system, but also induce severe nonlinear impairments, such as intermodulation effects of power amplifiers. In the proposed signal processing routine, the nonlinear signal processing is introduced.

The scheme is an iterative process, inclusive of the linear equalization, phase noise compensation, and nonlinear equalization [8, 9]. The linear equalization pilots are interleaved in the time domain. Then the signals in the frequency domain are compensated by simple estimation algorithms, such as the least squares algorithm. Next, the signal is re-modulated to the time domain by inverse fast Fourier transform (IFFT) operation, and the phase noise is compensated in the time domain using sub-sample fitting or interpolation algorithms. In the final step, the OFDM signal in the time domain is equalized with nonlinear filtering to mitigate the nonlinear impairments, where Volterra series-based filtering could be adopted. The truncated Volterra kernels up to third order are always considered, and the adaptive filtering algorithm, such as the recursive least squares algorithm, is used for the coefficients training. After nonlinear filtering, the signal is recovered back to the frequency domain. Finally, the user data is recovered by QAM de-mapping. According to the experimental analysis in [8, 9], two-step iteration is sufficient to make the receiving equalization algorithm converge to a stable stage, and the distortions can be well compensated.

Up to now, most nonlinear equalization algorithms mitigate the nonlinear impairments in the time domain, which causes a re-modulation process in the channel post-equalization, as shown in Fig. 4. It is time-consuming and may not "catch up" with the channel fluctuations of terahertz communications. Frequency domain nonlinear equalization with the same methodology as time domain nonlinear equalization is a meaningful research line for multicarrier-based terahertz communications. Furthermore, phase noise could also be compensated in the frequency domain. The laser phase noise exhibits Lorentz spectrum, where low-order Lorentz kernels dominantly contribute to the phase noise. Simple low-pass filtering on the Lorentz phase noise spectrum may improve the system robustness with low complexity.

Advanced Optoelectronic Terahertz Systems

Enabled by the broadband optoelectronic devices and advanced signal processing design, advanced optoelectronic terahertz systems could be set up and configured to achieve beyond 100 Gb/s rate.

Here, a multi-dimensional optoelectronic terahertz system architecture is presented in Fig. 4, which makes use of the multiplexing gain from the optical wavelength and antenna polarization domains [8, 9]. The solid lines represent the single-dimension terahertz communication system, and the dashed lines represent adding one extra parallel/orthogonal dimension in the system. A 30 GHz signal is modulated onto a phase modulator to generate an optical frequency comb. Then two phase-locked tones are selected as optical carriers. The IQ optical modulator is driven by the signal from an arbitrary waveform generator. After optical amplification, two baseband channels are separated, and a 1 m fiber delay line is used to de-correlate these two channels [9]. Another free-running laser, acting as a remote optical LO, is coupled with the optical signals after polarization alignment for generating THz signals, and the combined optical LO and signals are coupled into two paths leading to two UTC-PDs for heterodyne mixing-based generation of terahertz signals. Here, a longer than 1 m fiber delay line is used to de-correlate the data channels [9]. Two rectangular horn antennas are used. Here, the longer side of the rectangular antenna is along the horizontal polarization axis X, while the other is along the vertical polarization axis Y, to minimize the polarization crosstalk [9]. At the receiver side, the terahertz signal is individually down-converted to the intermediate frequency (IF) domain channel by channel with a Schottky mixer. The mixing output is amplified and fed into a broadband real-time digital storage oscilloscope (DSO). The proposed multicarrier signal processing routine is used for channel post-equalization.

In the single-dimension experiment, a 34.9 GHz PS-16-QAM-OFDM signal centered at a 350 GHz carrier is successfully transmitted over a 26.8 m wireless link with high-gain Cassegrain antennas; no multiplexing is employed. The experimental results reach 2.7E-2 soft decision forward error correction (SD-FEC) limit with 20 percent channel coding overhead to perform error correction, achieving 122.15 Gb/s raw line rate (3.5×34.9, including pilot overhead) [8], 119.1 Gb/s line rate (122.15/(1 + 1%)/(1 + 16/1024), excluding pilot overhead) and 99.25 Gb/s net rate (119.1/(1 + 20%), excluding pilot and FEC overhead). In the multi-dimensional experiment, 30×2 GHz PS-64-QAM-OFDM signals centered at 335 GHz and 365 GHz carriers are successfully transmitted over a 2 m line-of-sight wireless link with a pair of orthogonal polarization horn antennas. The experimental results reach 2.7E-2 SD-FEC limit, achieving a 628.44 Gb/s raw line rate (159.01 + 150.41 + 163.92 + 155.10), 612.65 Gb/s line rate, and 510.5 Gb/s net rate [9].

Discussions and Future Directions

In this subsection, we take our adopted scheme as an example to discuss current limitations, potential improvements, and further challenges, as many of these technical issues can be generically shared in other optoelectronic THz system variants.

An optical comb can be used to generate multiple coherent optical carriers to save the number of light sources and reduce the phase noise or frequency drift effect. The proposed system only uses the comb as the modulator's light source, and the optical LO originates from another laser, which deteriorates the performance improvement. Highly nonlinear optical modulators or materials (e.g., an Si3N4-based ring resonator) can be used to generate a broad and flat optical comb, from which the optical LO and optical modulation carriers can be selected.

The high-order mixer is used as the receiver, which may induce harmonic distortions to the IF signal. The externally biased balanced mixer with low-order frequency multiplier could be a substitute reception scheme.

High-gain Cassegrain antennas are bulky for mobile communications; they are more suitable for fixed-point access with extended reach requirements. For mobile communications, antennas must be smaller and efficient, so an antenna array could be used to enhance the transmitting power.

The future high-speed terahertz communication systems will not be a mere extension of current systems using separated devices, which are bulky and complicated. There are several fundamental aspects to push high-speed optoelectronic terahertz communications into applications.

To increase the data rates, a joint force between antenna array and multiple-input multiple-output signal processing ability is necessary. From the system level, making full use of the multiplexing gain from the optoelectronic domain is important, such as optical wavelength, and optical and electrical polarization. It is worth noting that complicated system work is a transition stage, and the eventual chip-scale work is crucial for driving real-world applications. Therefore, multi-dimensional multiplexing and processing chips are important for fully developing and making use of multiple physical dimension resources of photons, where silicon-based photonic integrated circuits [10] may play an important role in sustainable development of terahertz communications.

The migration of the aforementioned multi-dimensional system into a wireless access network needs to be considered. The baseband modulation could be merged into a central office (baseband unit), and the terahertz emitters could be

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Starting from the physical layer breakthroughs, more research work on the networking of terahertz links is a natural evolution. Medium access control protocol, application protocol, as well as the prototype networking architecture will pave the way to push terahertz treasure into the center stage of the information era.

merged into remote units in the radio-over-fiber infrastructure, which saves networking cost and enhances the centralized processing gain of wireless access network [15].

Conclusions and Prospects

We have analyzed application scenarios of high-speed optoelectronic terahertz communications, presenting technical insights into key technologies including terahertz photonics integrated circuits, the multicarrier baseband signal processing routine, and multi-dimensional system architecture, discussing the future directions on the device, signal, and system levels of optoelectronic terahertz communications.

There is still a long way to go toward real-world applications of terahertz communication technologies. Lucky things are that we could learn lessons from the millimeter-wave developments and develop the roadmap of terahertz communications. With the advances of photonics integration and application-specific integrated circuits, a terahertz pluggable terminal with large capacity and strong signal processing ability is expected to come to fruition. Starting from the physical layer breakthroughs, more research work on the networking of terahertz links is a natural evolution. Medium access control protocol, application protocol, as well as the prototype networking architecture will pave the way to push terahertz treasure into the center stage of the information era.

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