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Ultra-wideband fiber-THz-fiber seamless integration communication system toward 6G: architecture, key techniques, and testbed implementation

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Abstract Terahertz (THz) communication is widely regarded as the key component of future 6G mobile communication systems. Through comparative analysis of some of the main existing technical routes of THz up-conversion and down-conversion in THz wireless communication systems, a novel ultra-wideband (UWB) fiber-THz-fiber seamlessly converged real-time architecture, which utilizes the commercially mature digital coherent optical module to realize ultrahigh-capacity THz real-time wireless communication, is proposed in this study. (1) The proposed architecture employs the dual-polarization photonic up-conversion technique for THz generation and hybrid optoelectronic down-conversion technique for THz reception to facilitate the seamless integration between optical fiber and THz communications. (2) Because of the limited bandwidth of optoelectronic devices, multidimensional modulation techniques are adopted for UWB THz signals to improve spectral efficiency and transmission capacity. (3) An intelligent nonlinear joint compensation technique based on the deep neural network, which can effectively improve the signal-to-noise ratio of the time-varying hybrid fiber-THz-fiber channel, is proposed. Based on the investigations of the aforementioned key techniques, we, for the first time, realize the photonics-assisted record-high 100/200 GbE real-time THz wireless transmission at 360–430 GHz band, the capacity of which is 10–20 times higher than that of 5G. The proposed fiber-THz-fiber architecture can realize the smooth conversion between high-speed THz and lightwave signals. Moreover, the architecture can significantly reduce the research difficulty and development cost, thereby considerably accelerating the commercialization of 6G THz technology by thoroughly reusing commercial digital coherent optical module (DCO) modules, which are compatible with the physical layer transmission protocols, such as IEEE 802.3 and ITU-T G.798. Finally, this study also introduces some potential directions of research and development for higher-capacity, longer-distance, and more-integrated fiber-THz-fiber seamless communication.

Keywords 6G, THz wireless communication, optical fiber communication, seamlessly converged architecture, real-time communication

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1 Introduction

With 5G about to launch into the large-scale commercial stage around the world, 6G is becoming a new research hotspot of global information and communications technology; thus, several major countries and regions, such as China, the United States, the European Union, Japan, and South Korea, contributed to 6G research and development (R&D) [1]. In 2017, the European Union started to develop 6G terahertz (THz) communication technology with the support of the "Horizon 2020" plan. In 2019, the

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Federal Communications Commission of the United States generated the frequency band ranging from 95 GHz to 3 THz for future mobile communication applications and established the project to construct a high-speed THz wireless communication backbone network. In November 2019, the Ministry of Science and Technology of the People's Republic of China launched a 6G Key Technologies Research and Development Program for high-frequency millimeter-wave (mmW) and THz wireless communications. In 2020, the Japanese government established the 6G Technology Research Institute, and was motivated by some THz-related testing studies, trying to gain a first-mover advantage in the global 6G R&D. In 2019, the World Radio Communication Conference established the four globally identified frequency bands of 275–296 GHz, 306–313 GHz, 318–333 GHz, and 356–450 GHz for land mobile and fixed services, achieving 137 GHz bandwidth in total [2]. In 2019, China's IMT-2030 (6G) Promotion Group established the THz Communication Task Group, which will analyze the key technologies, application vision and standardization of THz communication as an important candidate technology for future 6G mobile communication. In December 2020, for the first time, Purple Mountain Laboratories, together with 50 experts from 24 research institutions and enterprises, proposed the 6G vision of "global coverage, all spectra, full applications, and strong security", which indicates that the THz and optical frequency bands would be the available candidate frequency bands for 6G [3]. In July 2021, the Institute of Electrical and Electronics Engineers established the THz Special Interest Group. In March 2022, in the 2nd "Global 6G Conference", the 6G THz topic was widely discussed, and one THz white paper was issued [4]. In summary, the industry and academia have reached a consensus about the 6G vision and technical route, and THz communication is widely regarded as the key component of future 6G mobile communication systems [5, 6].

The THz band (i.e., 300 GHz to 3 THz) has ultra-wideband (UWB) resources and can support ultrahigh wireless communication rates ranging from 100 Gb/s to even 1 Tb/s, which boosts the peak rate of existing 5G by one or two orders of magnitude. Moreover, the THz band can satisfy the demands of emerging bandwidth-hungry applications, such as ultrahigh-resolution holographic communication and metaverse [7, 8]. However, when the THz wireless communication capacity exceeds 100 Gb/s, which is close to the fiber channel capacity, the real-time processing of UWB wireless signals would be a key issue and challenge, because of the limitations of the bandwidth, sampling rate, and accuracy of high-speed digital-to-analog and analog-to-digital converters (DAC/ADC). Furthermore, the THz wave has relatively limited coverage because of its large air propagation loss, weak diffraction, and diffraction capability, which has been a large barrier in 6G THz communication.

In this study, a novel photonics-assisted fiber-THz-fiber seamlessly converged real-time architecture, which realizes UWB 6G THz real-time wireless communication utilizing the commercial digital coherent optical module (DCO), is proposed. The proposed architecture adopts both the dual-polarization (DP) photonic up-conversion for THz generation and the hybrid optoelectronic down-conversion for THz reception. The proposed architecture not only overcomes the inherent limitations of solid-state electronic devices in terms of bandwidth, characteristic frequency, and power efficiency but also facilitates the seamless integration between optical fiber and THz communications. To improve the spectral efficiency and transmission capacity, multidimensional modulation techniques for the UWB THz signal, which contribute to the Tbps-level THz communication system, are proposed. To overcome the bandwidth limitation of optoelectronic devices and nonlinear impairments of the integration system, an intelligent nonlinear impairment compensation algorithm based on the deep neural network (DNN), which can accomplish highly sensitive demodulation of the UWB THz signal and improve the signal-to-noise ratio (SNR) margin in a complex time-varying hybrid channel environment, is proposed. With the proposed fiber-THz-fiber seamlessly integrated real-time architecture, a real-time streaming platform with a single channel of 100 Gb/s and dual channel of 200 Gb/s at 360–430 GHz band, which exhibits the highest real-time THz transmission rate in the world, is established. The proposed architecture is composed of an integrated, flexible, easily deployed fiber-THz-fiber seamless system, which enables the distributed deployment of the optical fiber system and flexible access to the THz wireless system. Hence, the architecture not only solves the broad coverage issue of the large capacity THz system but also significantly reduces the 6G research difficulty and development cost, which considerably accelerates the commercialization process of 6G THz communication.

This paper is organized as follows: Section 2 presents the main research progress and technical route comparison. Section 3 elucidates the converged system architecture and key module design, including converged system architecture design, optical-THz (O-T) and THz-optical (T-O) conversion module design, and modulation techniques of UWB THz signals. Section 4 describes a 100/200 GbE real-time

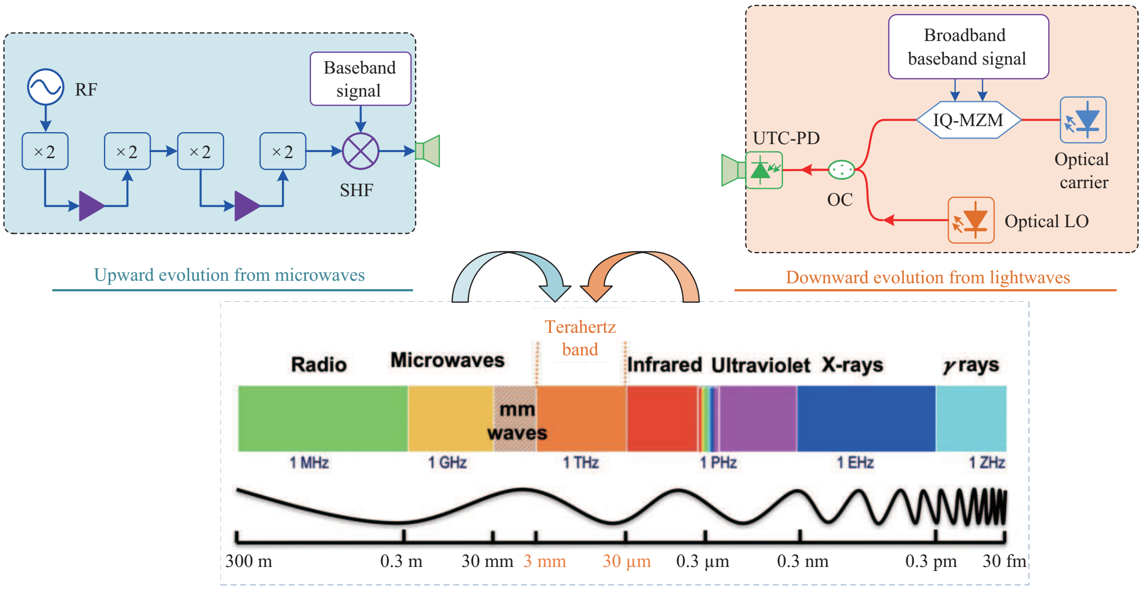

Figure 1 (Color online) Two technical routes for THz wireless communication.

transmission system. Section 5 presents future potential key R&D directions, including Tbps-level communication rate, km-level wireless transmission distance, core device chips, and integrated optoelectronic systems. Section 6 provides the conclusion.

2 Main research progress and comparison of technical routes

2.1 Two technical routes for up-conversion techniques

On the transmitter side of the THz wireless communication system, the conversion of the electrical baseband (BB) signal into the THz band is defined as THz up-conversion. According to the different principles of THz up-conversion, two technical routes are gradually formed in parallel, as shown in Figure 1. One is the all-solid-state electronic mixing technique, and the other is the photonics-assisted heterodyne beating technique. Table 1 lists the typical studies on all-electronics and photonics-assisted THz systems in recent years.

The electronic mixing technique adopts a "bottom-up" approach and generates a high-frequency THz signal by frequency multiplying a low-frequency microwave signal, which is the traditional technical route to achieve 6G THz wireless communications [9–19]. In 2011, Bell Labs generated a 625 GHz THz wave using an all-solid-state electric mixer, and transmitted a wireless rate of 2.5 Gb/s with a transmission power of 1 mW. Notably, 625 GHz is the highest carrier frequency thus far realized in the all-solid-state THz wireless communication system [14]. In 2015, the University of Stuttgart conducted an offline experiment to wirelessly transmit a 64 Gb/s THz signal over 850 m [16]. In 2017, the China Academy of Engineering Physics achieved ultra-long-distance THz communication with a wireless distance of up to 21 km; however, the transmission rate was only 5 Gb/s [18].

Meanwhile, the photonics-assisted heterodyne beating technique adopts an "up-bottom" approach and generates a high-frequency THz signal by heterodyne beating two lightwaves, which is an emerging technical route for 6G ultrahigh-speed THz wireless communications [20–35]. The photonics-assisted heterodyne beating technique route utilizes the inherent characteristics of optical devices, such as large bandwidth and high-frequency response, and combines multidimensional modulation techniques to break through the capacity bottleneck of the traditional technical route. In 2013, Nippon Telegraph and Telephone Corporation (NTT) established an offline single-carrier THz system with a 40 Gb/s rate and 1 m wireless distance using an ultrahigh-speed uni-traveling carrier photodiode (UTC-PD) [32]. The Karlsruhe Institute of Technology (KIT) launched an offline multicarrier THz system with a 100 Gb/s rate and 40 m wireless distance [20]. In recent years, Fudan University and Zhejiang University transmitted offline a 120 Gb/s [24] and a 600 Gb/s multicarrier THz signal with the aid of a 2×2 multiple-input multiple-output (MIMO) structure and the wavelength division multiplexing (WDM) mechanism, respec-

Table 1 Typical studies on all-electronics and photonics-assisted THz systems

Year	Country	Frequency (GHz)	Modulation	Data rate (Gb/s)	Distance (m)	Up-conversion techniques	Ref.
2011	Germany	220	OOK	2.5	0.5	Electronics, offline	[9]
2011	South Korea	240	ASK	1.485	4.2	Electronics, offline	[10]
2011	China	140	16QAM	10	500	Electronics, offline	[11]
2012	Germany	220	OOK	25	10	Electronics, offline	[12]
2014	Japan	300	QPSK	50	2	Electronics, offline	[13]
2011	USA	625	Duo-Binary	2.5	0.2	Electronics, real-time	[14]
2014	China	340	16QAM	3	50	Electronics, real-time	[15]
2015	Germany	240	QPSK	64	850	Electronics, real-time	[16]
2015	Japan	220	ASK	11	3	Electronics, real-time	[17]
2017	China	140	16QAM	5	21000	Electronics, real-time	[18]
2020	China	220	–	20	3600	Electronics, real-time	[19]
2013	Germany	237.5	16QAM	100	20	Photonics, offline	[20]
2017	UK	220–280	QPSK	100	0.7	Photonics, offline	[21]
2018	Denmark	141	16QAM	352	1	Photonics, offline	[22]
2019	Denmark	408	16QAM	131	10.7	Photonics, offline	[23]
2019	China	375–500	QPSK	120	1.42	Photonics, offline	[24]
2019	Germany	300	16QAM	128	0.5	Photonics, offline	[25]
2019	China	350	16QAM	60	4.5	Photonics, offline	[26]
2020	China	335–365	64QAM	600	2.8	Photonics, offline	[27]
2020	Germany	300	16QAM	132	110	Photonics, offline	[28]
2020	China	350	16QAM	100	26.8	Photonics, offline	[29]
2021	China	340	64QAM	44.8	104	Photonics, offline	[30]
2010	Japan	300	ASK	12.5	0.5	Photonics, real-time	[31]
2012	Japan	300	ASK	40	01	Photonics, real-time	[32]
2013	Japan	300	ASK	100	0.7	Photonics, real-time	[33]
2017	Germany	328	NRZ	6	1.5	Photonics, real-time	[34]

tively. In the aforementioned offline systems, the THz signals generated by the heterodyne beating of two free-running lasers would suffer from unstable carrier frequency and deteriorated phase noise, requiring complex carrier phase recovery algorithms in digital signal processing (DSP) modules at the receiver. One alternative is to use two correlated tones of an optical frequency comb (OFC) serving as the optical signal carrier and local oscillation light (LO). In this way, the phase noise of the obtained THz signals can be considerably reduced by the heterodyne beating two homologous beams, which in turn significantly reduces the complexity and power consumption of the required DSP routine. The Technical University of Denmark successfully transmitted a 106 Gb/s THz signal at 0.5 m [35] and 131 Gb/s THz signal up to 10.7 m [22] using a modulator-based OFC and an integrated homologous laser, respectively. In the past two years, KIT and Fudan University successfully transmitted a 132 Gb/s 16QAM signal [28] and a 44.8 Gb/s PS-64QAM signal [30] at the THz band, respectively. The wireless transmission distances were effectively enhanced to be more than 100 m with the assistance of a high-gain THz amplifier or high-gain lens antenna.

2.2 Comparison of two THz up-conversion techniques

Through the above analysis, Table 2 summarizes the advantages and disadvantages of the two THz up-conversion routes. The all-solid-state electronic mixing route has a small size and low power consumption and can be easily integrated. Moreover, the transmission power of the THz signal can reach the mW level with the aid of an effective power amplifier; hence, the THz wireless transmission distance can reach up to km level, as shown in Figure 2. This is a significant advantage for the all-solid-state electronic mixing route. However, because of the inherent properties of electronic devices, the parameters of high-frequency electronic devices gradually approach the theoretical limit. Thus, the transmission bandwidth is relatively low, resulting in the maximum transmission rate not exceeding 100 Gb/s. By contrast, the photonics-assisted heterodyne beating technique can generate a higher carrier frequency and wider adjustable range; thus, it is superior in terms of THz transmission rate, which can reach up to hundreds of Gb/s or even Tb/s. However, the THz signal power generated by heterodyne beating is usually limited to the mW level because of the lower responsivity of the UTC-PD, resulting in a shorter THz

Table 2 Comparison of typical THz up-conversion techniques

Up-conversion technique	Data rate	Distance	Signal quality	Frequency tunability	Integration with fiber network
All-solid-state electronics mixing	Low	Long	Low	Fixed	Difficult
Photonics-assisted heterodyning	High	Short	High	Flexible	Easy

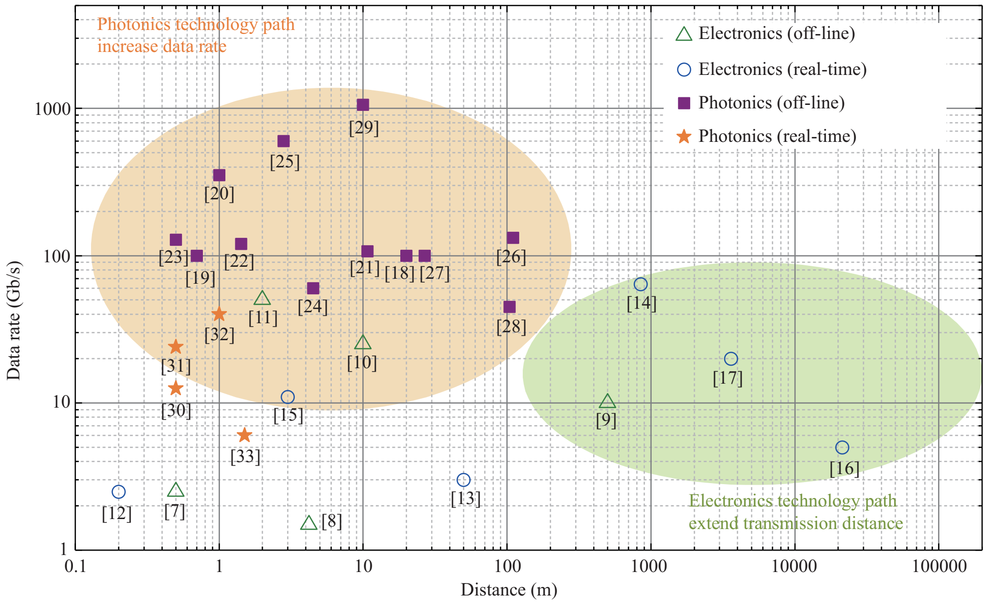

Figure 2 (Color online) Typical studies on THz wireless communication systems.

wireless distance. Fortunately, the wireless distance can be enhanced to more than 100 m with the aid of high-gain THz amplifiers or high-gain lens antennas. Notably, in the application scenarios of future 6G mobile communications, the hm-level wireless transmission distance can meet its coverage requirements. Therefore, the photonics-assisted THz route, which can support hundreds of Gb/s and even Tb/s communication rates, is undoubtedly a better choice.

2.3 Three technical routes for down-conversion techniques

At the receiving side of the THz communication system, the conversion of the received THz signal into the BB is defined as THz down-conversion. Figure 3 shows three feasible techniques for THz down-conversion, namely, all-electric down-conversion, all-optical down-conversion, and hybrid optoelectronic down-conversion. Table 3 [20,36,38–43] lists the research works on the three THz down-conversion routes in recent years.

First type. All-electric down-conversion converts the received THz signal into the electrical BB signal. As shown in Figure 3(a), all-electric down-conversion is implemented by mixing the THz signal with the THz LO via a monolithic microwave integrated circuit (MMIC)-based THz mixer. The THz LO is obtained by N frequency multiplying a radio frequency (RF) source. If further integrated with the optical communication system, then the electrical BB signal needs to be converted again into an optical baseband signal via an I/Q (in-phase/quadrature) modulator. In 2013, KIT realized a wireless bridge system at 237.5 GHz band using an MMIC-based receiver. The bridge system transmitted a 75 Gb/s 8QAM signal over a 40 m wireless distance [20]. In 2020, the Fraunhofer Heinrich Hertz Institute successfully achieved 100 Gb/s net rate real-time transmission at a 300 GHz band over two spans of fiber and a 0.5 m wireless link using an MMIC-based receiver and DCO [36]. Notably, the "all-electric down-conversion method" defined here is different from most existing THz communication systems. Most systems only focused on the point-to-point THz transmission without further considering the seamless integration of the THz wireless communication with an optical fiber wired network. Therefore, at the receiving end, most systems first down-converted the received THz signal to the intermediate frequency (IF) band, then further down-converted the IF signals into the I/Q electrical BB in the digital domain after AD sampling, and finally equalized the electrical BB for demodulation and data recovery. If the aforementioned systems are further connected to an optical fiber link, then the I/Q electrical BB signals

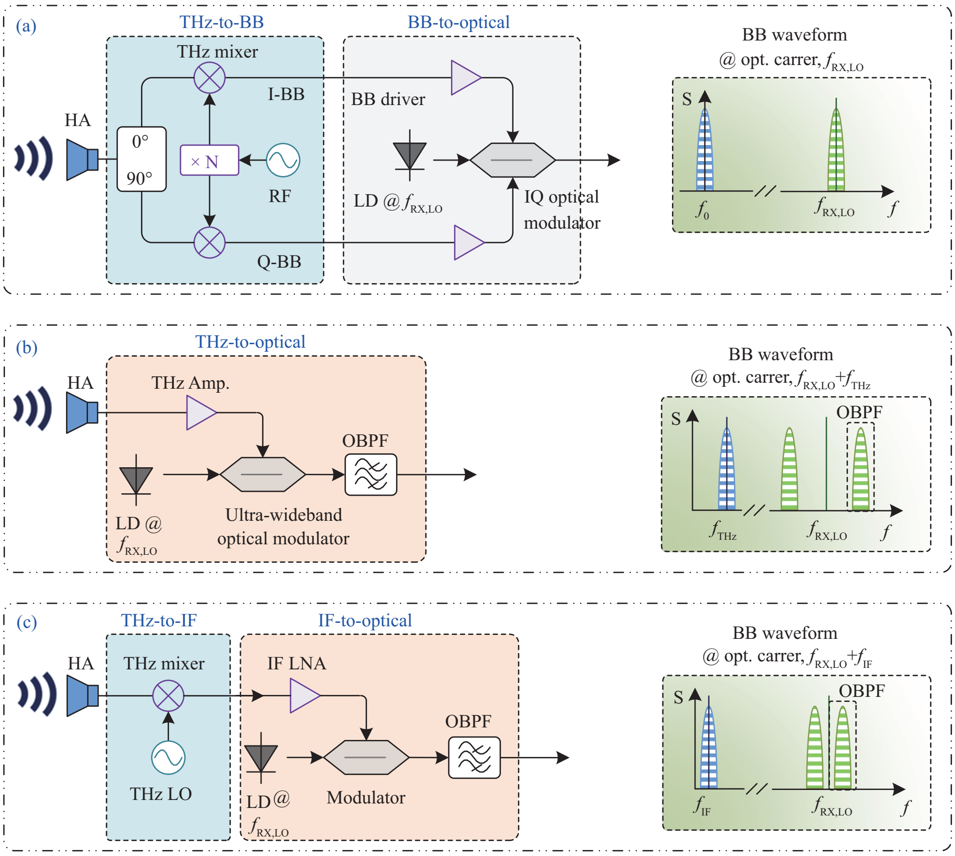

Figure 3 (Color online) THz down-conversion techniques. (a) All-electric down-conversion; (b) all-optical down-conversion; (c) hybrid optoelectronic down-conversion.

in the digital domain need to be requantified by DA conversion and converted into optical BB signals by loading into an I/Q modulator. The aforementioned complex and expensive AD/DA conversion process is unsuitable for the proposed THz-fiber integrated architecture.

Second type. All-optical down-conversion converts the received THz signal into the optical BB signal. As shown in Figure 3(b), the received THz signal directly modulates the optical carrier to generate two optical sidebands through a UWB THz electro-optic modulator. Then, one of the sidebands is filtered out as the optical BB signal via an optical band-pass filter [37–40]. In 2019, KIT achieved a 50 Gb/s communication rate over a 16 m wireless distance using their developed plasmonic silicon modulator with a bandwidth exceeding 360 GHz [38]. In 2021, the Institute of Technology Zurich demonstrated a 240 Gb/s transparent fiber-THz-fiber transmission system over 115 m wireless distance at 231 GHz via a UWB plasmonic Mach-Zehnder modulator (MZM) [39]. In 2022, the Japanese NTT demonstrated a fiber-mmW-fiber transmission system at a 100 GHz band using a low-loss thin-film lithium niobate based phase modulator. The system successfully transmitted a 71.4 Gb/s 64QAM signal over the hybrid channels which consist of two fiber links and a 20 m wireless link [40].

Third type. The hybrid optoelectronic down-conversion technique also converts the received THz signal into the optical BB signal. As shown in Figure 3(c), the THz signal is down-converted into the IF signal, which corresponds to the first step of the down-conversion process. Then, the IF signal is modulated on the optical carrier by an electro-optic modulator, and the optical BB signal is obtained by filtering out one of the optical sideband signals using an optical filter, which corresponds to the second step of the down-conversion process [41–43]. In 2018, at Fudan University, Yu et al. [41] reported an offline fiber-THz-fiber transmission system at 450 GHz using hybrid photoelectric down-conversion at the THz receiver side, which experimentally transmitted a QPSK (quadrature phase-shift keying) signal of 13 Gb/s over two spans of fiber links and a 20 m wireless link. In the same year, this team increased the offline system capacity to 18 Gb/s using the 2×2 MIMO structure [42]. In 2021, the University College London, UK, verified a photonic-assisted wireless bridging system using hybrid optoelectronic down-conversion technique at a 250 GHz band, and successfully achieved 50 Gb/s 16QAM signal wireless

Table 3 Typical studies on the three kinds of THz down-conversion techniques

Year	Country	Frequency (GHz)	Modulation	Data rate (Gb/s)	Distance (m)	Down-conversion technique	Ref.
2013	Germany	237.5	16QAM	100	40	All-electric, offline	[20]
2020	Germany	300	QPSK	100	0.5	All-electric, real-time	[36]
2019	Germany	288.5	QPSK	50	16	All-optical, offline	[38]
2021	Switzerland	231	QPSK	240	115	All-optical, offline	[39]
2022	Japan	100	64QAM	71.4	20	All-optical, offline	[40]
2018	China	450	QPSK	13	3.8	Hybrid optoelectronic, offline	[41]
2018	China	450	QPSK	18	3.8	Hybrid optoelectronic, offline	[42]
2021	UK	250	16QAM	50	0.1	Hybrid optoelectronic, offline	[43]

Table 4 Comparison of the typical THz down-conversion techniques

Down-conversion technique	Structure complexity	Maturity	Signal quality	Cost	Integration with fiber network
All-electronic	High	Medium	Low	Low	Low
All-optical	Low	Low	High	High	High
Hybrid optoelectronic	Medium	High	Medium	Medium	Medium

transmission over two spans of fiber links and a 0.1 m wireless link [43]. Notably, the aforementioned offline studies have a low transmission rate, which does not fully exploit the potential advantages of the hybrid optoelectronic down-conversion technique.

2.4 Comparison of the three THz down-conversion techniques

By comparison, in the case of the all-electric THz down-conversion, the RF source suffers from large loss and seriously deteriorated phase noise because of frequency multiplication; thus, the harmonic mirror interference needs to be suppressed. Moreover, MMIC I/Q mixers above 350 GHz are not technically mature, and the THz-fiber conversion structure is relatively complex. Therefore, it is difficult for the all-electric down-conversion method to be highly integrated with the optical communication system. Conversely, as shown in Table 4, the all-optical down-conversion and hybrid optoelectronic down-conversion techniques have their own pros and cons. The all-optical down-conversion technique considerably reduces the complexity of the T-O conversion module and avoids the serious insertion loss and spurious noise of the THz LO caused by the frequency multiplication of the RF source. However, extending the electro-optic modulator to the THz band is complicated, resulting in higher fabricating costs and lower qualification rates. The existing studies on the THz modulator are all in the laboratory verification stage, which is still a long way from commercialization [44, 45]. Even though the hybrid optoelectronic down-conversion technique can induce some insertion loss and phase noise because of electric mixing in the process of down converting the THz signal into the IF signal, the impairments can be effectively compensated with advanced DSP algorithms at the receiver side. To achieve full-scene coverage and low-cost deployment for future 6G mobile communications, the hybrid optoelectronic down-conversion solution is still a preferred technical scheme because it is simple, inexpensive and highly feasible.

3 Converged system architecture and key module design

3.1 Converged system architecture design

Based on the previously presented comparative analysis, a novel fiber-THz-fiber seamlessly converged real-time architecture, which adopts both DP photonic up-conversion for THz generation and hybrid optoelectronic down-conversion for THz reception, is proposed in this study. As shown in Figure 4, through both the O-T conversion module at the THz transmitting side and the T-O conversion module at the THz receiving side, seamless integration and flexible switching can be realized between optical fiber wired communication and THz wireless communication. At the THz transmitting side, a pair of UTC-PDs in the O-T conversion module realizes DP photonic up-conversion; thus, the polarization division multiplexing baseband (PDM-BB) signal is converted into two channels of THz signals carrying x-polarized and y-polarized BB information. After the 2×2 MIMO THz wireless transmission, the two channels of THz signals are received by a pair of THz antennas at the THz receiving side and reconverted into PDM-BB optical signals on the T-O conversion module via the hybrid optoelectronic

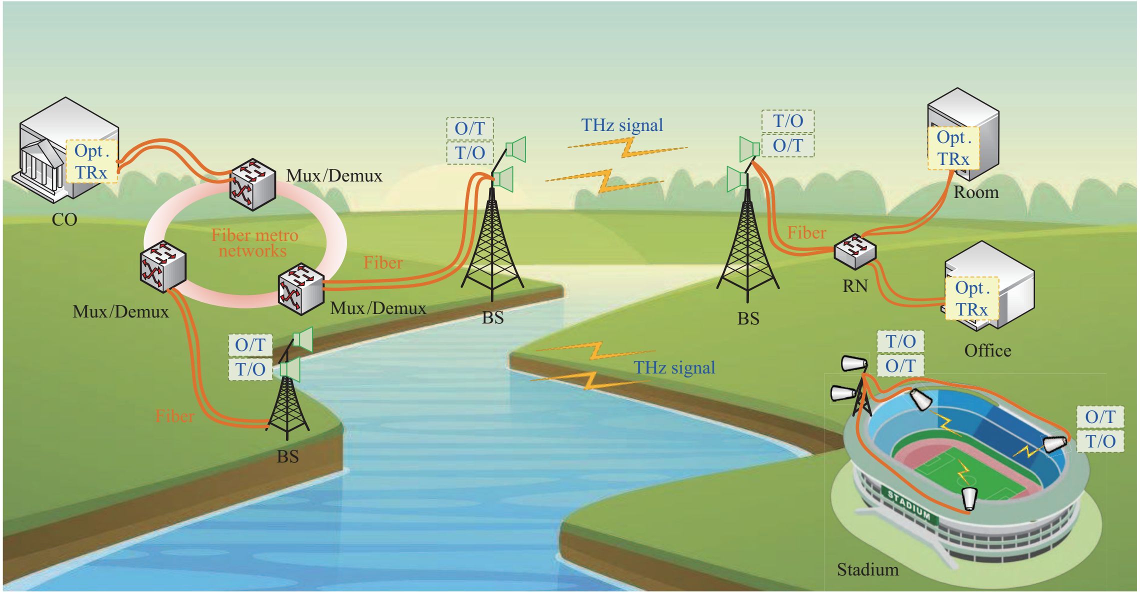

Figure 4 (Color online) Fiber-THz-fiber seamlessly converged system architecture.

down-conversion. To realize a 6G UWB seamless fiber-THz-fiber communication system, the following key technologies are proposed.

• **UWB fiber-THz-fiber seamlessly converged real-time architecture.** When the THz wireless communication capacity exceeds 100 Gb/s, the real-time processing of UWB THz signals has been a key issue and challenge. R&D of a high-speed real-time wireless signal transceiver module demands considerable time and money investments, and the FPGA-based transceiver module is characterized by a large size and high power consumption, which severely restricts the practical and commercial process of the UWB THz real-time communication system. By contrast, with the rapid development of optical fiber communication, the real-time reception technology of UWB optical signal has increasingly matured, and the DCO module has been highly integrated; thus, the real-time communication rate can reach up to 800 GbE. For the first time, the fiber-THz-fiber real-time transmission architecture, which is seamlessly integrated with the current rapidly developing optical fiber communication, is proposed. The proposed architecture considerably accelerates the commercialization of 6G THz technology by thoroughly reusing commercial DCO modules, which are compatible with the physical layer transmission protocols, such as IEEE 802.3 and ITU-T G.798 (refer to Subsection 3.1).

• **DP photonic up-conversion technique for THz generation and hybrid optoelectronic down-conversion technique for THz reception.** In most of the existing photonics-assisted THz communication systems, the all-electronic down-conversion technique is adopted on the receiving side, and previous studies do not consider the integration with high-speed optical transmission links. The system architecture design in the aforementioned studies is relatively simple and cannot meet the urgent requirements of indoor and outdoor continuous coverage of 6G THz communication in the future. The DP photonic up-conversion technique is adopted in this study for THz generation to facilitate the joint DP multiplexing in the optical fiber and THz 2×2 MIMO spatial multiplexing, which effectively improves the spectral efficiency and transmission capacity of the THz transmission system. The hybrid photoelectric down-conversion technique is proposed for THz reception, which facilitates flexible switching between THz and lightwave signals and significantly reduces the research difficulty and development cost of the THz wireless communication system. Based on these two techniques, the seamless integration issue of the fiber-THz-fiber transmission is solved systematically (refer to Subsections 3.2 and 3.3).

• **Multidimensional modulation techniques for UWB THz signals close to the Shannon theoretical limit.** The UWB THz modulation signals, particularly if they are close to the Tbps-level transmission rate, usually require a higher baud rate and larger transmission bandwidth. However, the UWB THz signal quality often deteriorates due to the limited bandwidth of commercial optoelectronic devices in this transmission system. Most of the existing photonics-assisted THz transmission systems always simply and independently adopt the multiplexing, constellation shaping, or high-order modulation technology and do not consider the adaptability of the modulation format to the variation of the hybrid fiber-THz channel. Hence, there is a certain gap in the system capacity from the Shannon limit. In this study, a multidimensional modulation technique is proposed for the UWB THz signal. Specifically, according to the actual situation of the hybrid fiber-THz channel, the hybrid constellation shaping technology is adopted based on end-to-end self-coding learning to adjust the position and distribution probability of the constellation points adaptively to maximize the system transmission capacity. The pulse shaping technique is used to compress the spectral bandwidth of the PDM-BB signal, improve the spectral efficiency, and reduce the intersymbol interference (ISI) caused by the limited bandwidth of photoelectric devices. Multidimensional multiplexing techniques, such as WDM, PDM, and MIMO space division multiplexing (SDM), are used to improve the spectral efficiency and transmission capacity of the integration system, the capacity of which further approaches the Shannon transmission limit. The multidimensional multiplexing techniques can help achieve Tbps-level THz transmission for 6G (refer to Subsection 3.4).

• **Intelligent nonlinear impairment compensation techniques for the hybrid fiber-THz channel.** The hybrid fiber-THz channel discussed in this study exhibits complex time-varying characteristics. In particular, when the THz wireless distance covers as far as over 100 m or even 1 km, the received signals suffer from multiple severe linear and nonlinear impairments caused by various optoelectronic devices and hybrid THz-fiber channels. Each impairment deteriorates the SNR of the received signals, and these multiple impairments would be superimposed together, which further limits the communication performance of the system, making it difficult for traditional conventional digital equalizers to efficiently compensate for these nonlinear impairments of the hybrid channels. Therefore, an intelligent DNN-based impairment compensation technique is proposed. With its sensing and self-adaptive capabilities, the proposed DNN-based compensation technique can accurately extract the high-dimensional nonlinear distortion component, accomplish highly sensitive demodulation of the UWB THz signal in a complex time-varying hybrid channel environment, and effectively address the SNR limitation issue of the hybrid channels. The proposed compensation techniques could contribute to 100-m or km-level THz wireless transmission (refer to Subsection 3.5).

The seamless integration system, with the combined advantages of optical and THz communications, can be widely used in various UWB wireless access and alternative fiber scenarios on the ground to save the cost of fiber laying and achieve rapid network deployment and recovery. The integration system can also be mounted on space-borne platforms, such as satellites, unmanned aerial vehicles, and airships, to be seamlessly connected to large-capacity optical networks through ground transceiver stations, thus realizing 6G ultrahigh-speed air-space-ground multidimensional integrated THz communications. Moreover, the integration system can realize the full security potential of wireless THz and wired fiber to achieve end-to-end secure communications in a wide area. The flexible switching of the fiber-THz-fiber architecture considerably improves the scalability and adaptability of short-distance high-performance THz wireless communications. Through seamless integration with widely distributed long-distance and high-capacity optical networks, the fiber-THz-fiber architecture ensures that photonic-assisted THz technology becomes an important support for future social information fusions and interconnections.

3.2 Design of O-T conversion module

In the central office, an off-the-shelf commercial DCO module is used to generate a dual-polarized optical I/Q BB signal with a carrier frequency of fs (Figure 5(c) inset a). The DCO compatible with the IEEE 802.3 and ITU-T G.798 physical layer transmission protocols supports 100 GbE Ethernet and OTU4 signal processing, respectively. The data information to be transmitted is first preprocessed by a 7-nm DSP chip built in the DCO, then undergoes analog-to-digital conversion by a high-speed DAC, and finally drives the integrated coherent transmitter.

At the THz transmitter, as shown in Figure 5(a), the O-T conversion module adopts dual-polarized photonic up-conversion to facilitate the joint multiplexing of DP fiber transmission and THz 2×2 MIMO space transmission, effectively improving the spectral efficiency and transmission capacity of the THz transmission system. Specifically, the optical BB signal with a carrier frequency of f_s, and the local oscillator lightwave (LO1) with a carrier frequency of f_{LO1}, are coupled together by an optical coupler (OC) (Figure 5(c) inset c). The coupled signals are divided into x-polarized and y-polarized BB signals (Figure 5(c) insets d and e) after passing through an erbium-doped fiber amplifier (EDFA) and a polarization beam splitter (PBS). Notably, two polarization controllers before the OC are used to adjust the polarization of the orthogonally polarized BB signal and the LO1, so that the polarization states

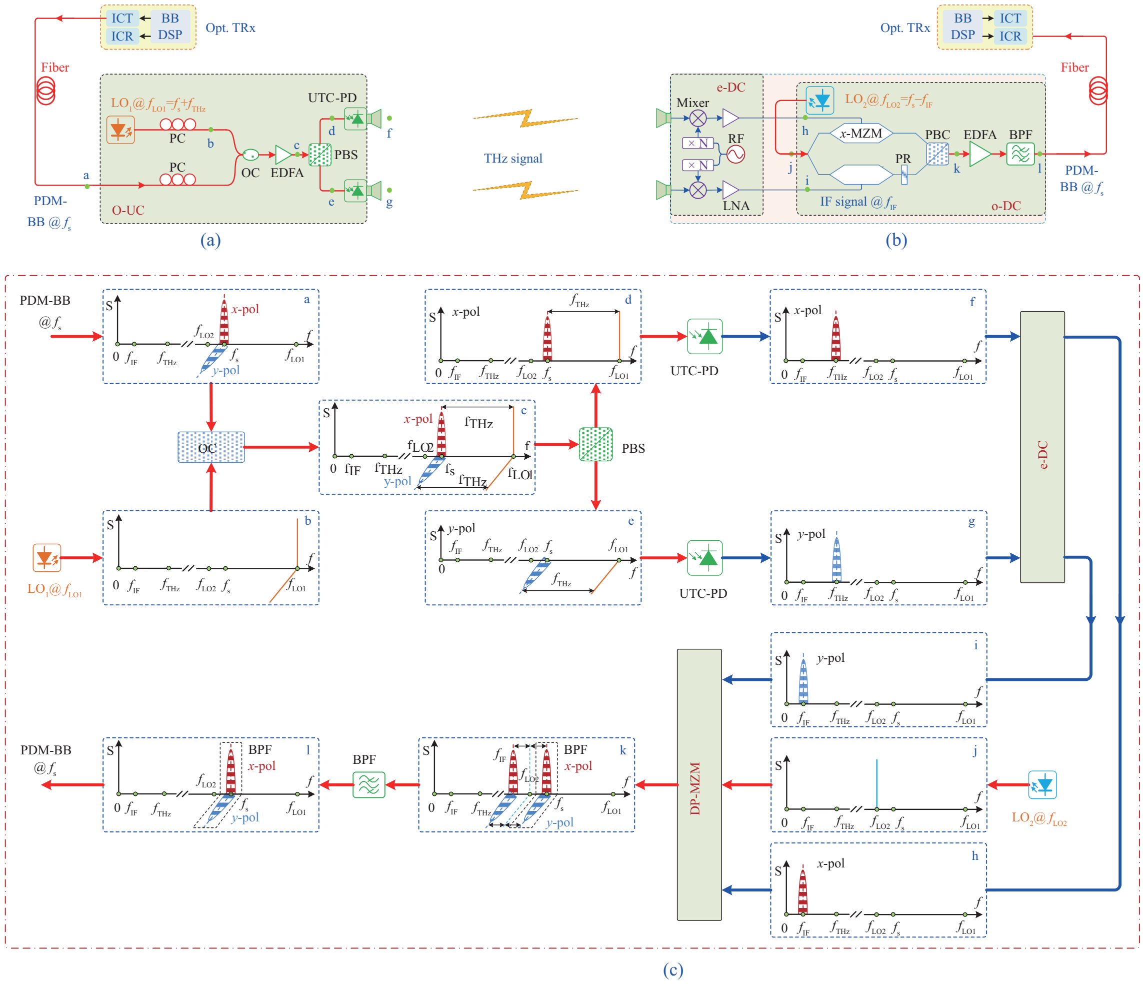

Figure 5 (Color online) Key modules. (a) O-T conversion module; (b) T-O conversion module; (c) spectra diagram of up-conversion and down-conversion.

of the two beams are well aligned with the respective PBS, thereby reducing the polarization splitting loss as much as possible. Based on the optical heterodyne mechanism, the x-polarized and y-polarized BB signals are converted into two THz signals (@$f_{\mathrm{THz}} = f_{\mathrm{LO1}} - f_s$, Figure 5(c) insets f and g) by two UTC-PDs and radiated into free space via two THz antennas.

3.3 Design of T-O conversion module

At the THz receiver, as shown in Figure 5(b), the T-O conversion module adopts the hybrid photoelectric down-conversion to facilitate flexible conversion from the THz signal to the optical BB signal, which is a high-maturity and low-cost feasible solution for the integration system.

The THz signal is down-converted into the IF signal in the electrical down-conversion (e-DC) module, which corresponds to the first step of the down-conversion process. After being transmitted over the wireless link, the THz signals from two polarization branches are received by a pair of THz antennas. The local RF source performs N frequency doubling and is mixed with the received THz signals to generate two IF signals (@$f_{\mathrm{IF}} = |f_s - f_{\mathrm{LO2}}|$). Afterward, the IF signals are amplified by corresponding low-noise amplifiers. This is the e-DC process of the THz signal.

Furthermore, the obtained electrical IF signals are converted into the optical BB signals in the optical down-conversion module, which corresponds to the second step of the down-conversion process. As shown in insets h and i of Figure 5(c), the two IF signals, as the driving signals of the x-polarized and y-polarized modulators (x-MZM and y-MZM, respectively), are simultaneously modulated on the local oscillator lightwave (LO2) with the frequency of f_{LO2}, as shown in inset j of Figure 5(c). Thus, a double-sideband optical signal with carrier suppression is generated, as shown in inset k of Figure 5(c).

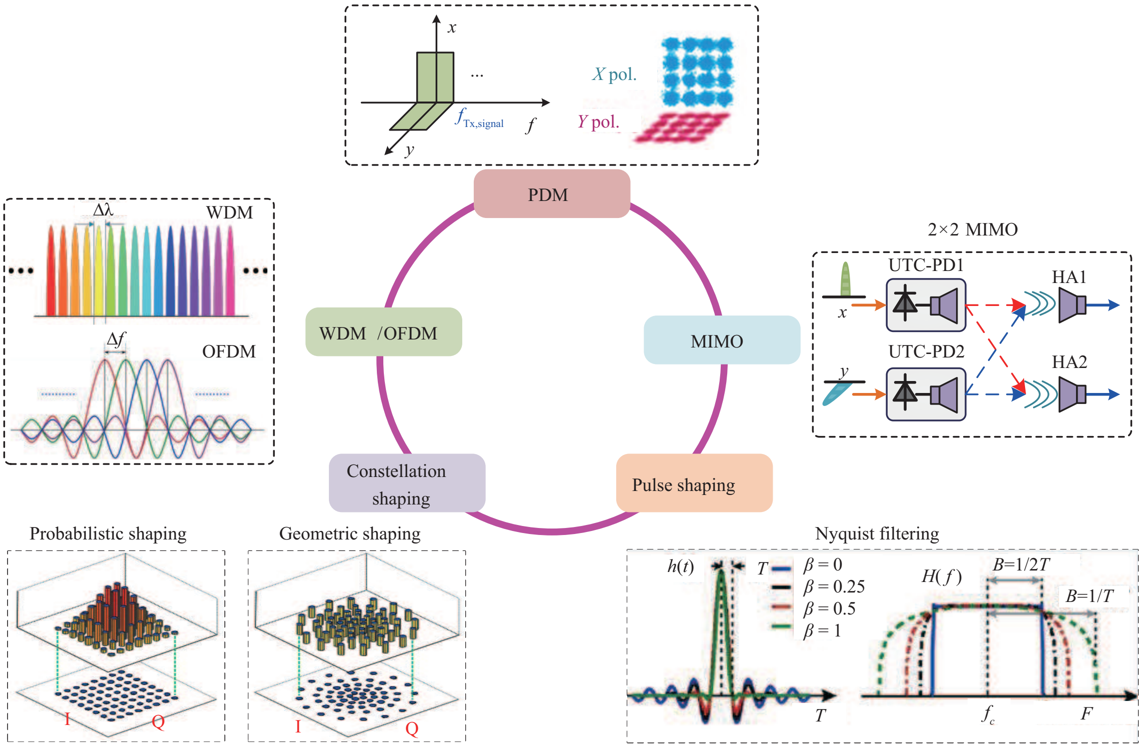

Figure 6 (Color online) Five dimensions of high spectral efficiency and ultra-wideband THz signal modulation.

After being amplified by another EDFA, a band-pass filter is used to filter out the upper sideband and suppress the amplified spontaneous emission noise outside the band to output the optical PDM-BB signal ($@f_s = f_{\rm LO2} + f_{\rm IF}$), as shown in inset l of Figure 5(c). This is the optical down-conversion process of the IF signal.

Finally, the obtained optical PDM-BB signal is input into the commercial DCO module for real-time signal processing after long-distance transmission over fiber links. In the DCO module, a built-in integrated coherent receiver (ICR) that contains 90° optical hybrids and balanced detectors performs photodetection of the received optical BB signal. After analog-to-digital conversion by ADCs, the obtained digital signal is input into the built-in 7-nm DSP chip for clock recovery, channel equalization, dispersion compensation, MIMO polarization demultiplexing, and carrier phase recovery to recover the desired digital BB information.

3.4 Modulation techniques of UWB THz signals

In the case of the limited bandwidth of optoelectronic devices, the baud rate of the THz signal needs to be reduced through multidimensional modulation to improve the spectral efficiency and system capacity and realize a photonics-assisted THz system with a rate beyond 100 Gb/s or even 1 Tb/s. As shown in Figure 6, for a THz-fiber hybrid channel, this study presents five modulation dimensions for spectrum-efficient and UWB THz signals, which fall into three main categories according to different technical fields.

First type. Both the constellation shaping and pulse shaping techniques belong to the digital domain signal processing. The traditional probability shaping (PS) and geometric shaping (GS) techniques try to reveal the Gaussian distribution characteristics of the channel by changing the probability of constellation points (without changing the position of constellation points) and the geometric position of constellation points in the complex plane (without changing the probability of constellation points), respectively [46]. Thus, a higher transmission rate close to the Shannon limit of the transmission system can be achieved. In particular, the PS technique optimizes the probability of constellation points by directly changing a single parameter to match different channels. Because the positions of constellation points remain unchanged, the PS method is easily compatible with the classical DSP algorithm, resulting in stable and efficient performance. However, the traditional PS and GS techniques lack self-adaptability and have disadvantages such as large optimization granularity under the complex time-varying THz-fiber hybrid channel. The proposed hybrid constellation shaping based on end-to-end self-encoding learning can adaptively adjust the position, distribution probability, and mapping relationship of constellation points according to the actual situation of the hybrid THz-fiber channel to maximize the transmission capacity of the integration system. The Nyquist pulse shaping technique is used to further compress the spectral bandwidth of the BB signal by reducing the filter roll-off coefficient, thereby improving the spectral efficiency and reducing the demand for the device bandwidth; however, it will lead to ISI at the same time. Therefore, a trade-off optimization is required between the roll-off factor and DSP complexity. By simultaneously optimizing the hybrid constellation shaping and Nyquist pulse shaping techniques, the spectral efficiency and transmission capacity of the hybrid THz-fiber system can be further improved.

Second type. Both the PDM and MIMO SDM techniques have diverse multiplexing characteristics. In the hybrid THz-fiber system, optical PDM diversifies and multiplexes the x-polarized and y-polarized BB signals in the same spectrum space, effectively increasing the system capacity by two times. Meanwhile, at the THz transceiver, the multi-antenna structure of 2×2 MIMO instead of the single-antenna structure of the single-input single-output system is used, so that the THz signals with different polarization states are transmitted over two air paths and received by two different antennas. These two diverse multiplexing techniques, i.e., optical PDM and MIMO SDM, can be well unified in the hybrid THz-fiber system.

Third type. Both the WDM and frequency division multiplexing techniques fall into the frequency domain. To improve the transmission capacity of the hybrid THz-fiber system, the WDM technique is adopted to simultaneously transmit multiple optical signals of different wavelengths on one fiber. In the T-O conversion module, the THz signal of multiple frequency bands is generated by the optical heterodyne mechanism with multiple optical signals of different wavelengths, thus significantly increasing the air interface rate of a single antenna. Moreover, affected by fiber dispersion and atmospheric turbulence, the hybrid THz-fiber channels suffer from frequency-selective fading. Compared with the traditional single-carrier modulation format, coherent optical orthogonal frequency division multiplexing (CO-OFDM) has significant advantages, such as anti-dispersion, high sensitivity, good flexibility, and strong channel adaptability. Based on the real-time detected SNR of the hybrid channels, the CO-OFDM technique can adaptively allocate different QAM orders and transmit powers to each subcarrier to achieve bit and power loading, thus further improving the spectral efficiency and capacity of the hybrid THz-fiber system.

3.5 Demodulation techniques of UWB THz signals

Because the fiber-THz-fiber seamless integration communication system operates in the THz frequency band, and the hybrid fiber-THz-fiber channel exhibits complex and time-varying characteristics, the transmission signal suffers from various impairments, such as power attenuation of the optical fiber and atmosphere, optical fiber nonlinearity, polarization coupling rotation effect, and MIMO-ISI. Meanwhile, the signal quality would deteriorate because of the bandwidth limitation, filtering effect, laser linewidth, frequency offset, and jitter caused by photoelectric devices in the system. All the aforementioned linear and nonlinear impairments reduce the SNR, and these multiple impairments together can further limit the communication performance of the system. Thus, it is difficult for the traditional digital equalizers based on the fixed compensation and recovery algorithm to effectively obtain the accurate high-dimensional nonlinear distortion component and efficiently compensate for these nonlinear impairments of the hybrid channels.

Therefore, in this study, an intelligent nonlinear impairment compensation technique is proposed for various complex nonlinear impairments in the hybrid fiber-THz channel. As shown in Figure 7, the lookup table (LUT) nonlinear pre-distortion and time-domain digital pre-equalization are adopted in the DSP routine of the transmitter side. Meanwhile, the Volterra and DNN nonlinear equalization techniques are combined in the DSP routine of the receiver side. In the DSP routine of the transmitter side, the obtained symbols after symbol mapping of the information-bearing data sequence are processed through LUT nonlinear pre-distortion and upsampling. Then, the modulated PDM-BB signal can be generated after digital pre-equalization and resampling. Notably, the LUT nonlinear pre-distortion and time-domain digital pre-equalization can overcome the ISI issue caused by the nonlinearity and bandwidth limitation of optoelectronic devices, respectively [47]. After transmission through the optical fiber and THz wireless channel successively, the x-polarized and y-polarized BB signals are received by the ICR, sampled by the ADC, and resampled and clock recovered in the digital domain in the DSP routine of the receiver side [48]. Subsequently, an optimized constant modulus algorithm (CMA) is adopted to

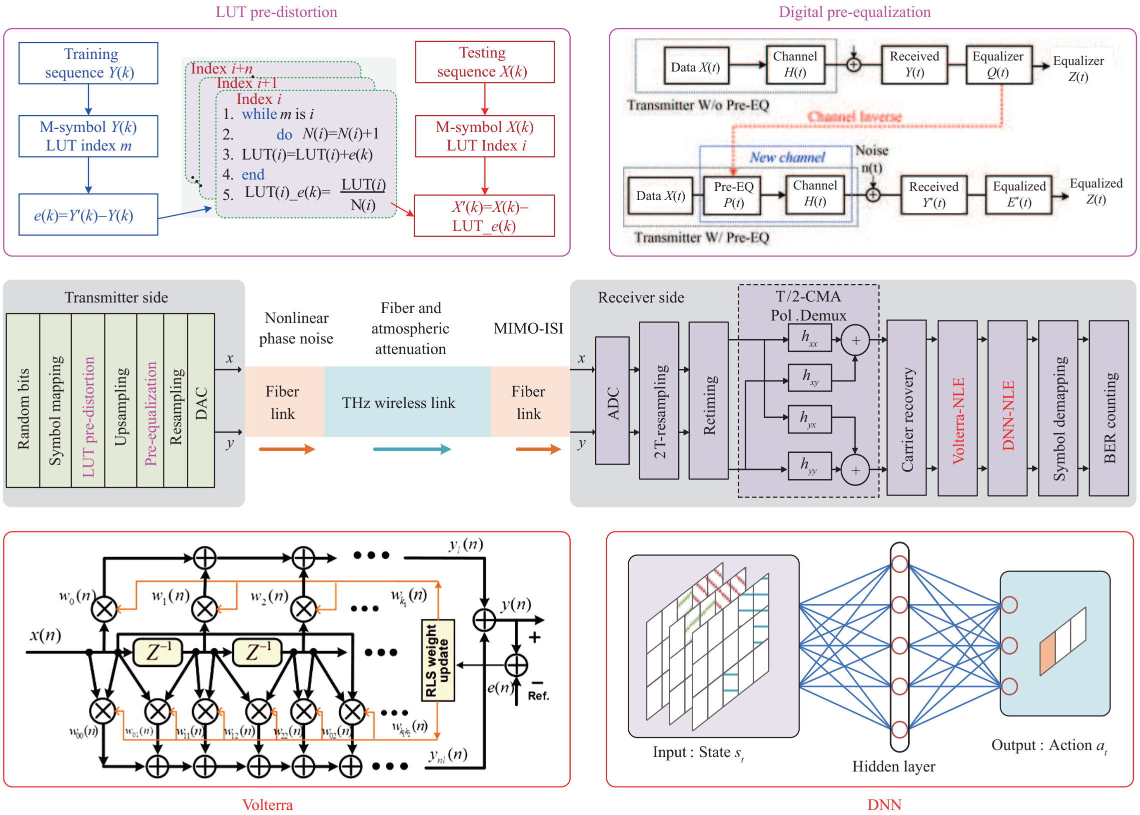

Figure 7 (Color online) Intelligent nonlinear damage compensation techniques for THz-fiber hybrid channels.

address polarization demultiplexing and polarization mode dispersion compensation and can rapidly and accurately obtain the convergence coefficient and reduce the complexity of the traditional CMA. For carrier recovery, first, the frequency offset estimation based on the fourth power algorithm is adopted and then the Viterbi-Viterbi phase estimation algorithm is used for phase recovery to compensate for the signal impairment caused by the laser linewidth. Before obtaining the symbols, the second-order Volterra nonlinear equalizer can be used to compensate for the time-varying first-order linear and second-order nonlinear distortions. For the time-varying high-dimensional nonlinear distortions, the intelligent DNN adaptive equalization can further realize the complex compensation [49]. The adopted DNN has multiple hidden layers, where the nonlinear activation functions can extract high-dimensional feature components with limited hidden layer numbers. For different signal modulation formats, according to the actual influence induced by the hybrid fiber-THz channel, the optimized trade-off needs to be considered comprehensively among the system's overall performance, including the compatibility and efficiency of the aforementioned equalization algorithms, to eventually achieve the highly sensitive demodulation of the UWB THz signal.

4 Demonstration of the 100/200 GbE real-time transmission system

A 100/200 GbE 2×2 MIMO real-time transmission platform was developed based on the proposed fiber-THz-fiber system architecture and key techniques. As shown in Figure 8 [50], the demonstration system consists of the following parts: (1) 100/200 GbE streaming platform; (2) O-T conversion module; (3) T-O conversion module. At the THz transmitter side, O-T conversion is based on the DP photonic up-conversion technique. The hybrid optoelectronic down-conversion technique is used for T-O conversion at the THz receiver side. The 100/200 GbE streaming platform consists of the streaming server, displayers, optical transmission unit (OTU), and client server. Four 4K surveillance cameras are connected to the streaming media server via an Ethernet switch and a modem with TCP/IP protocol, which can support real-time surveillance video service. The 100 GbE network card in the streaming server is connected to the OTU through a QSFP28 module supporting 4×25.78125 Gb/s. The CFP2-DCO modules in the

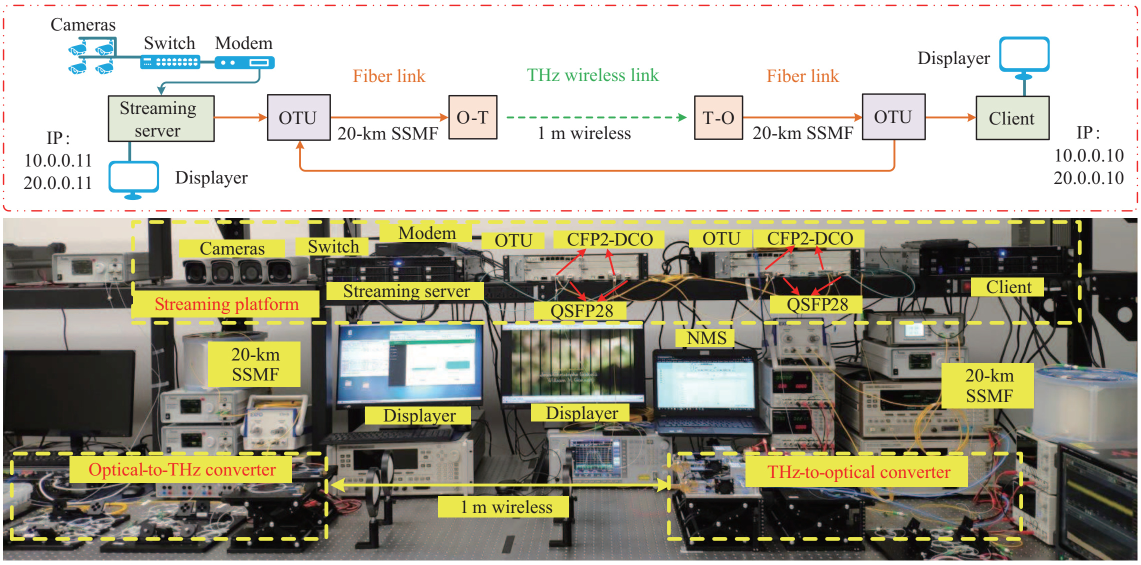

Figure 8 (Color online) Demonstration of the 100/200 GbE real-time transparent fiber-THz-fiber 2 × 2 MIMO transmission system [50].

OTU are compatible with the IEEE 802.3 and ITU-T G.798 physical layer transmission protocols, which can support 100 GE Ethernet and OTU4 signal processing, respectively. Furthermore, the CFP2-DCO modules can support high-speed real-time polarization diversity homodyne detection and DP-QPSK demodulation with a built-in 7 nm DSP chip. The CFP2-DCO parameters, such as operating mode, wavelength, optical power, and pre-bit error rate (pre-BER), can be set and monitored on the network management system interface of the OTU. The DCO adopts a typical 15% soft-decision forward error correction (15% SD-FEC) channel coding and decoding method, with a net coding gain of 10.8 dB, which not only supports high-speed real-time polarization diversity homodyne detection and demodulation but also conforms to the ITU G.709 standard.

For the 100 GbE real-time transmission testbed, the joint multiplexing method of DP transmission and 2 × 2 MIMO spatial transmission is used. The CFP2-DCO module in OTU works at 100 GbE mode with 125.516 Gb/s line rate (i.e., 103.125 Gb/s net rate) and can generate optical BB signals with 31.379 GBaud DP-QPSK modulation format and 0.2 roll-off factor. Hence, the signal bandwidth can be computed as $31.379 \times (1 + 0.2) = 37.6548$ GHz. At the O-T conversion side, the carrier frequency of the optical signal is set at 193.5 THz, and the center wavelength of the local oscillator LO1 is tuned to generate THz-wave wireless signals with frequencies ranging from 360 to 430 GHz. The optical spectra at the O-T conversion side are shown in Figure 9(a) [51, 52]. At the T-O conversion side, the THz-wave signals are converted into the optical BB signals using the hybrid optoelectronic down-conversion technique. To avoid spectrum aliasing and high-frequency power fading, the optimal IF after down-conversion is set at 24 GHz, as shown in Figure 9(b). Considering the 15% SD-FEC threshold (i.e., pre-FEC BER $= 1.56 \times 2^{-2}$, post-FEC BER $< 10^{-15}$), the single-wavelength net rate 103.125 Gb/s transmission is achieved at 360–430 GHz over two spans of 20 km fiber and 1 m THz wireless distance. As shown in Figure 9(c), at the 15% SD-FEC threshold, the optical signal-to-noise ratio margins in the back-to-back and hybrid fiber-THz channel cases are 5.3 and 1.7 dB at 370 GHz, respectively. Finally, the real-time streaming platform exhibits a stable performance after the 2-h stability test, as shown in Figure 9(d).

For the 200 GbE real-time transmission testbed, two DFP2-DCO modules based on the WDM technique operate in the 100 GbE mode. The two channels are compatible with the ITU-T 50 GHz grid; hence, their carrier frequencies are set at 193.5 and 193.55 THz, corresponding to Channel 1 (Ch1) and Channel 2 (Ch2), respectively. At the O-T conversion side, the local oscillator LO1 works at 193.116 THz, and the THz frequencies of Ch1 and Ch2 are 384 and 434 GHz, respectively, as shown in Figure 10(a). At the T-O conversion side, the two channels are filtered, demodulated, and tested by tuning the RF clock frequency. As shown in Figure 10(b), when the input optical power of UTC-PD is 12.8 dBm, the error floor of THz signals is 1.8×10^{-3} at 384 GHz and 2.5×10^{-3} at 434 GHz, and the corresponding OSNR (optical signal-to-noise ratio) upper bound are 14.6 and 13.9 dB, respectively. These results show

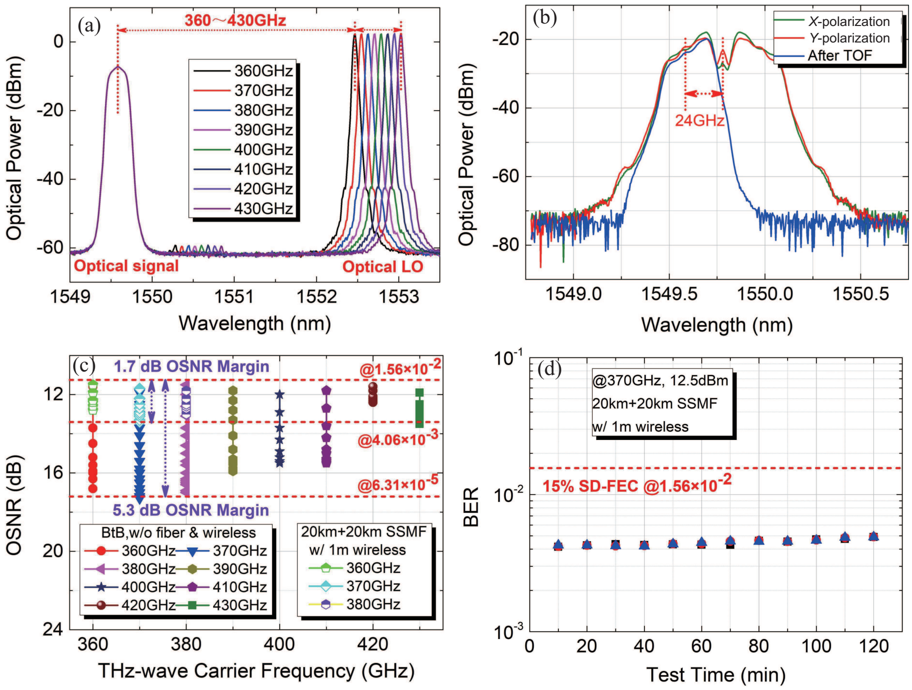

Figure 9 (Color online) Test results of the 100 GbE real-time fiber-THz-fiber transmission. (a) Spectra at the O-T side; (b) spectra at the T-O side; (c) performance of OSNR; (d) transmission stability test results [51, 52].

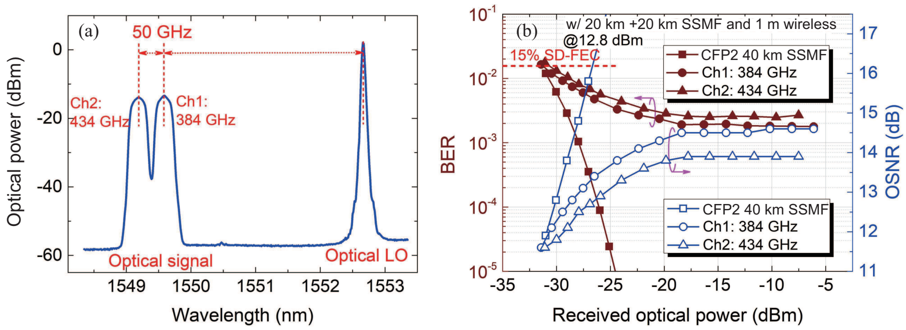

Figure 10 (Color online) Test results of the 200 GbE real-time fiber-THz-fiber transmission. (a) Spectra at the O-T side; (b) BER and OSNR versus received optical power for two channels.

that, in the case of hybrid channel transmission with two spans of 20 km fiber and 1 m THz wireless distance, a THz signal with a net rate of 2×103.125 Gb/s is successfully transmitted on the testbed. Because the SD-FEC channel coding and decoding algorithm with a net coding gain of 10.8 dB, is adopted by the CFP2-DCO module, the demonstrated system has preferable random and burst error correction capabilities in mobile scenarios, particularly under complex interference.

5 Future key R&D direction

5.1 Tbps-level communication rate

In December 2020, Purple Mountain Laboratories released a white paper on 6G research, in which it proposed that the 6G peak rate will be up to 1 Tb/s and pointed out that the large-scale application of THz wireless communication is inseparable from the support of large-capacity optical fiber transmission networks [53]. Thus far, the publicly reported photonics-assisted THz systems, which benefitted from the inherent characteristics of optical devices, such as high frequency and large bandwidth, can achieve an offline rate of up to 300 Gb/s on a single optical carrier [27]. However, there are still many challenging issues to further developing UWB photonics-assisted real-time communication and increasing the peak rate of the THz system to the Tbps-level. By integrating the UWB THz modulation techniques in five dimensions (i.e., WDM, PDM, MIMO, constellation shaping, and pulse shaping) and combining the intelligent nonlinear impairment compensations for the time-varying hybrid channels, it is expected to break through the capacity upper limit of the hybrid THz-fiber channels and realize Tbps-level THz real-time communication.

5.2 Kilometer-level wireless transmission distance

To realize long-distance and ultrahigh-speed wireless transmission scenarios, the photonics-assisted THz wireless transmission distance needs to be increased to the km level to facilitate the full-scene coverage of the THz-fiber integration communication. At present, limited by the low photoelectric conversion efficiency of UTC-PD, the transmitting power of the THz signal generated by beating two lasers is usually in the order of microwatts; thus, the wireless transmission distance is limited to tens of meters. For the THz frequency above 300 GHz, the high-gain and large-bandwidth amplification technology would be the problem-resolving key. The THz power amplification and low-noise amplification techniques, which are enabled by InP-based heterojunction bipolar transistors/double heterostructure bipolar transistors, can not only increase the transmission power of THz signals from tens of microwatts to hundreds of milliwatts but also effectively improve the receiver sensitivity for those weak THz signals. Eventually, the THz wireless transmission distance of the hybrid system could be extended. To overcome the transmission attenuation in free space and achieve directional transmission and reception of THz signals, the THz phased array technique is also an important development direction. This technique is also the key to realizing 6G THz mobile communication, which meets the needs of application scenarios, such as multiple users and beam tracking. For the THz phased array, it is important to suppress the beam squint of the THz phase-shifting system and accurately delay the ultra-bandwidth THz signal; these aspects will be the key research points.

5.3 Core device chips and integrated optoelectronic system

At the THz transmitter, the typical detection responsivity of the commercially available UTC-PD is 0.15 A/W, and the transmitted THz power is only in the order of microwatts, which seriously limits the communication capacity and transmission distance of the hybrid fiber-THz system. To improve the photoelectric conversion efficiency of UTC-PD, some efforts, including optimizing the impurity concentration of each layer of semiconductor materials in UTC-PD and designing a high-efficiency coupling structure with broadband matching and low insertion loss, could be applied. To simplify the structure of the THz receiver side, reduce the cost, and promote the seamless integration of THz wireless and optical fiber links, R&D of the DP plasmonic electro-optic modulator with ultra-large bandwidth, low insertion loss, and low half-wave voltage needs to be conducted. How to reduce the fabricating cost and complexity and improve the qualification rate still needs to be addressed in the future.

Thus far, photonics-assisted THz systems have been generally developed using discrete devices with low integration, resulting in large system volumes, high power consumption, and high costs. InP-based and Si-based optoelectronic integration are the two most commonly used integration routes. The InP-based optoelectronic integration has an excellent RF performance and high characteristic frequency (200–500 GHz) but is only suitable for the integration of small-scale optoelectronic devices because of the limitations of waveguide loss, wafer size, and transistor type. By contrast, the Si-based optoelectronic integration has a larger wafer size, lower manufacturing cost, smaller waveguide loss, and more abundant transistor types. Moreover, the Si-based optoelectronic integration is compatible with the CMOS process, making it more suitable for large-scale optoelectronic integration. Heterogeneous integration based on the 3D packing technique can organically combine the unique advantages of the InP-based and Si-based processes, which will shorten the interconnection length, reduce transmission loss, increase the RF bandwidth, and considerably improve integration performance. Specifically, it stacks multiple chips in the vertical direction based on the flip chip and through-silicon via processes. With the advanced chip integration and packaging techniques, the volumes of the photonics-assisted THz system can be significantly reduced, and the energy efficiency can be considerably improved. Hence, the system performance can be significantly improved, which would promote the practicability and commercialization of the THz-fiber integration system.

6 Conclusion

The photonics-assisted THz technology has all the potential to overcome a series of "electronic bottleneck" problems, such as large frequency conversion loss and limited frequency and bandwidth in traditional all-electronic THz wireless communication systems. In this study, an ultrahigh-speed fiber-THz-fiber seamless integration communication system is systematically investigated based on the photonic up-conversion and hybrid optoelectronic down-conversion techniques. Using maturely commercial DCO, this architecture can break through the limitation of the traditional wireless communication system in terms of the bandwidth, sampling rate, and resolution of high-speed DAC/ADC. Thus, 6G ultrahigh-capacity THz real-time wireless communication can be realized. A detailed system architecture, core modules, and key techniques for the proposed fiber-THz-fiber seamless integration communication system are introduced in detail and experimentally verified in this study. The experimental results show that this architecture can support the net rate of single-channel 103.125 Gb/s and dual-channel 206.25 Gb/s real-time 2×2 MIMO wireless communication, which realize the highest real-time THz wireless communication and improve the communication rate by 10 to 20 times compared with 5G. Moreover, by resorting to commercial DCOs, which are compatible with the IEEE 802.3 and ITU-T G.798 physical layer protocols, the proposed fiber-THz-fiber system can significantly reduce the technical limitation and cost of 6G R&D, thereby promoting the commercialization of 6G THz technology. At the same time, by utilizing the advantages of low-loss transmission and flexible deployment of optical fiber communication, the coverage and application scenarios of THz communication can be expanded. Finally, the future development trend of the fiber-THz-fiber integration communication system is explored in terms of three advanced objectives, namely, large capacity, longer distance, and higher integration.

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