Tbit/s Multi-Dimensional Multiplexing THz-Over-Fiber for 6G Wireless Communication

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***Abstract*—Photonics-aided terahertz (THz) wireless systems have been progressively developed to accommodate the forthcoming wireless communication with extremely high data rates in recent years. However, restrained by the obtainable signal-to-noise ratio (SNR) and the dimensions explored in THz photonic wireless systems, achieving data rates of Tbit/s and beyond is still challenging. In this paper, we present a multi-dimensional multiplexing Tbit/s THz-over-Fiber wireless communication system, by efficiently benefiting from the multiplexing gain in both optical wavelength and space domains. Enabled by a combined routine of an optical frequency comb, a low inter-core crosstalk (IC-XT) multi-core fiber and advanced digital signal processing, a line rate of up to 1176 Gbit/s over a wireless distance of 10 m in the 350 GHz band is experimentally demonstrated without any THz amplifiers, resulting in a net data rate of up to 1059 Gbit/s. To the best of our knowledge, this is the first time that beyond Tbit/s wireless data rate is successfully achieved in the THz region above 300 GHz, making a significant contribution to the development of THz-over-Fiber systems for the sixth generation (6G) wireless communication.**

***Index Terms*—Multi-core fiber, multi-dimensional multiplexing, sixth generation, terahertz photonics, terahertz communication.**

I. INTRODUCTION

OVER the past decades, the explosive growth of data traffic has been well-witnessed in the wireless communication networks. Currently, millimeter-wave band (30-300 GHz) has been adopted in 5G communication networks, which is expected to reach the data rates of 10 Gbit/s and continue boosting. According to the Cisco report [1], the number of Internet users are predicted to exceed 5 billion by 2023. Besides, both wireless and mobile data rates are anticipated to boost threefold from 2018 to 2023. To sustain this growth trend, wireless data transmission with beyond 100 Gbit/s and eventually Tbit/s is of vital essence. However, such high data rates are still difficult to be obtained based on current millimeter-wave communications since the total consecutive available bandwidth of that is less than 10 GHz. The terahertz (THz) band (0.3-10 THz) featuring very large bandwidth is hereby recognized as a promising candidate to accommodate the ever-increasing data traffic for 6G wireless networks [2],[3].

In recent years, THz wireless communication systems have evolved rapidly, and photonics-aided THz communication links have so far achieved some impressive results, with a special dedication in driving high capacity [4]–[14]. Benefit from the large available bandwidth of optoelectronic devices and low propagation loss of optical fibers, photonics-aided THz communication systems can not only enhance the data rates of wireless transmission, but also bridge the wireless frontends with optical access networks seamlessly. For example, by utilizing a single optical wavelength and spectrally efficient modulation formats, photonic wireless transmission of 100 Gbit/s at 280 GHz, 106 Gbit/s at 400 GHz and 128 Gbit/s at 300 GHz over a distance of 0.5 m have been experimentally demonstrated [4]–[6]. To further enable the data rates exceeding 100 Gbit/s, some multiplexing techniques such as wavelength division multiplexing (WDM) and polarization multiplexing (PDM) have been individually employed in sub-THz/THz wireless communication systems. For instance, a 100 GHz communication link with 108 Gbit/s based on PDM [13], a data rate of 260 Gbit/s at 400 GHz based on WDM method [14] have been achieved. Please note WDM is usually translated to frequency division multiplexing (FDM) in the wireless domain by photomixing-based frequency conversion. These single dimensional multiplexing schemes have indeed significantly contributed to the development of high-speed THz communications, however not sufficient to support wireless data rates approaching Tbit/s and beyond, which is not yet achieved in the THz region above 300 GHz. This is mainly limited by the obtainable signal-to-noise ratio (SNR) after hybrid photonic wireless transmission, particularly caused by atmospheric propagation loss in the THz frequency region.

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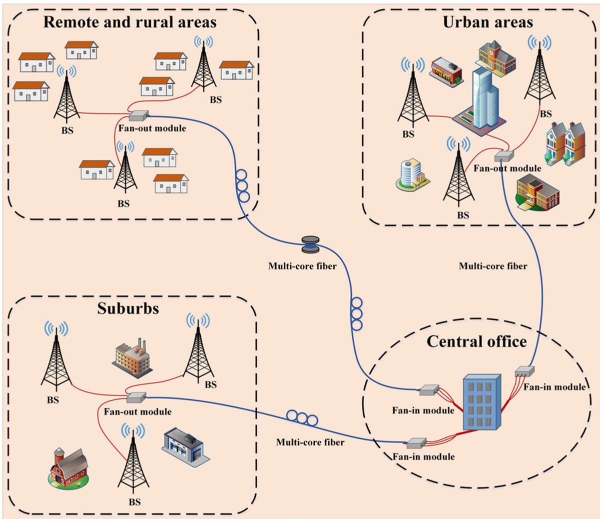

Fig. 1. A typical application scenario based on THz-over-multicore-fiber technology. BS: base station.

Here, we propose and experimentally demonstrate a multi-dimensional multiplexing scheme aiming to deliver Tbit/s and beyond data rates by exploring the multiplexing gain in both optical wavelength and space domains. In our system, a cutting-edge uni-traveling carrier photodiode (UTC-PD) [14] featuring fast response time and high output saturation current is employed for generating THz signals, and a high sensitivity Schottky diode heterodyne mixer is used to down-convert the THz signal. The transparency of heterodyne photo-mixing in the generation scheme makes the dimensions available in the optical domain beneficial for the wireless. Combining an optical frequency comb (OFC), 16-ary quadrature amplitude modulation format (16-QAM), a low inter-core crosstalk (IC-XT) multi-core fiber and advanced digital signal processing (DSP) routine, we demonstrate an aggregated net data rate of up to 1059 Gbit/s over a wireless distance of 10 m in the 350 GHz band. The signal bandwidth in each core is within that of THz receiver for simultaneous reception, and the overall data rate beyond 1 Tbit/s is the highest data rate in the THz band above 300 GHz, which is expected to open a door towards Tbit/s for 6G wireless networks.

One of the typical application scenarios envisioned utilizing THz-over-Fiber technology is shown in Fig. 1. A central office is deployed to centrally implement such as baseband processing and optical generation of signals, and then the optical signals are coupled into multi-core fibers via fan-in modules. After transmission through the multi-core fibers, the signals are extracted by fan-out modules core-by-core, which can be then distributed over the single mode fiber links and destined to endusers in such as the remote and rural areas, urban areas, suburbs, and so on. Here a multi-core fiber-based link is considered as the ultra-high-speed infrastructure in future optical fiber networks providing an additional space dimension infrastructure. In this manner, the THz wireless and optical fiber access network architecture are seamlessly connected, which can not only boost the capacity of wireless access, but also provide great network resilience and flexibility.

II. THz Multi-Dimensional Multiplexing Wireless Communication Link

A. Experimental Setup

The conceptual multi-dimensional multiplexing THz-over-Fiber wireless communication system is displayed in Fig. 2(a). Here, a wavelength demultiplexer is employed to line-by-line separate OFC frequency components for subsequent WDM strategy. After data modulation, the modulated signals are group-combined via wavelength multiplexers, which are then individually launched into each core of multi-core fiber by a fan-in module. After the transmission through multi-core fiber and extraction via a fan-out module, the output signals from each core are then connected to a base station (BS) to wirelessly cover one area, where an unmodulated light and a THz transmitter are employed to implement photomixing-based opto-electronic conversion and wireless radiation.

Fig. 2(b) depicts the experimental configuration of multi-dimensional multiplexing THz-over-Fiber wireless transmission with Tbit/s data rate. Firstly, we use an external cavity laser (ECL1, $<$100 kHz linewidth) to generate a 1550 nm continuous wave (CW) light. Then the light is launched into a polarization controller (PC1) and a phase modulator (PM), where the PM is driven by an amplified RF sinusoidal signal. The sinusoidal signal is generated from a vector signal generator (Keysight, E8267D) with an output power of 12 dBm at 15 GHz, and then is amplified by a RF amplifier with 18 dB gain before driving the PM. The PC1 is employed to adjust the polarization state of the incident light from the ECL1, to maximize the polarization dependent modulation efficiency of the PM. The optical spectra of OFC after the PM is shown in Fig. 3(a), measured with a high resolution optical complex spectrum analyzer (APEX, AP2683B). The resolution is set to 0.8 pm (equivalent to 100 MHz). The center wavelength of the OFC is 1550 nm and the wavelength space between the optical comb lines is 15 GHz. From the Fig. 3(a), the carrier-to-noise ratio of the middle 3-line is the largest, which is more than 40 dB. Therefore, three optical comb lines, at 1549.88 nm, 1550 nm and 1550.13 nm, are selected and filtered out by a programmable wavelength selective switch (WSS, FINISAR, WaveShaper 4000A) for the WDM. After the amplification by an Erbium-doped fiber amplifier (EDFA1), the three selected optical comb lines are launched into an in-phase and quadrature optical modulator (IQ-MOD) to implement the complex digital baseband modulation (16-QAM), where the PC2 is used to optimize the polarization state of three optical carriers. Here an arbitrary waveform generator (AWG, Keysight, M8195A) with 65 GSa/s sampling rates is employed to generate a pseudo-random binary sequence (PRBS) with a word length of 2^{15}-1 for user data, and its baud rates is adjustable. The output voltage of the AWG is set to 80 mV, which is amplified by two electrical amplifiers (RFA2, RFA3) with 26 dB gain for driving the IQ-MOD. The three modulated optical signals are then divided into seven copies by a 1×7 splitter and coupled into a piece of 7-core fiber through a fan-in module. In the experiment, a low IC-XT 7-core fiber with a length of 1 km is employed to transmit high-speed communication signals. Compared with standard single-core fiber transmission, this 7-core fiber can

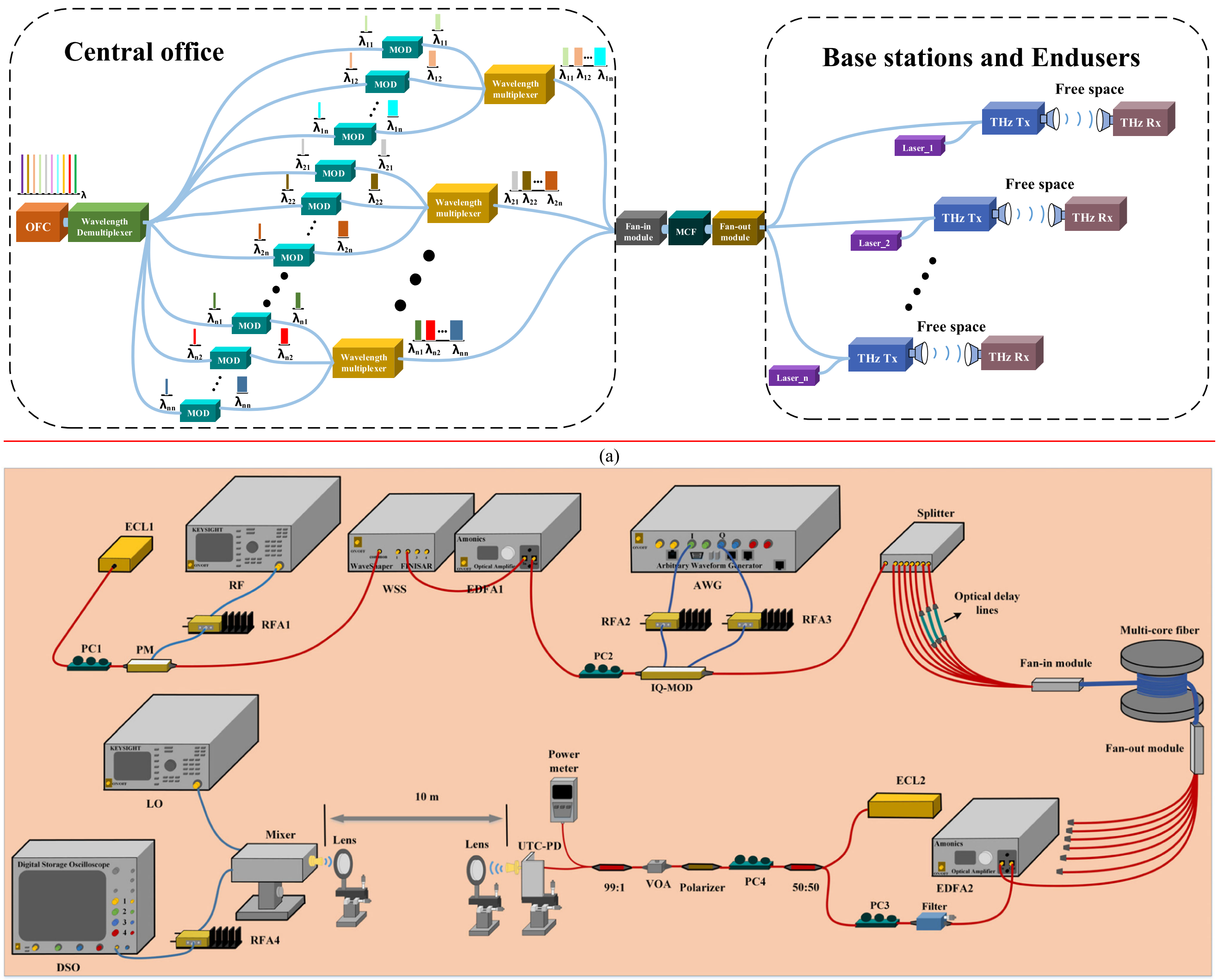

Fig. 2. (a) The conceptual multi-dimensional multiplexing THz-over-Fiber wireless communication system. (b) Experimental configuration of Tbit/s multi-dimensional multiplexing photonic wireless transmission link. OFC: optical frequency comb; MOD: modulation; MCF: multi-core fiber; Tx: transmitter; Rx: receiver; ECL: external cavity laser; PC: polarization controller; PM: phase modulator; RF: radio frequency; RFA: RF amplifier; WSS: wavelength selective switch; EDFA: erbium-doped fiber amplifier; AWG: arbitrary waveform generator; IQ-MOD: in-phase and quadrature modulator; VOA: variable optical attenuator; UTC-PD: uni-traveling carrier photodiode; DSO: digital storage oscilloscope; LO: local oscillator.

transmit multiple optical signals simultaneously in a single fiber with space domain multiplexing, which significantly boost the communication capacity.

The cross-section view of the 7-core fiber is shown in Fig. 4(a). For the light beams centered at 1550 nm, the attenuation is around 0.25 dB/km each core. The average core pitch and cladding diameter of the 7-core fiber are 41.5 μm and 8 μm, respectively. Besides, the chromatic dispersion and the IC-XT are around 17.1 ps/nm/km and -50 dB/100 km, respectively. In addition, the fan-in/fan-out modules shown in Fig. 4(b) hold a crosstalk between adjacent cores of -55 dB and insertion loss of around 1 dB, respectively, to establish a low-loss and reliable connection between the splitter and the 7-core fiber. Data decorrelations in the spatial channels are performed by the optical delay and dispersion. After 1 km 7-core fiber transmission, the output signal from each core is independently boosted by another EDFA2, and filtered by an optical band-pass filter to suppress the out-of-band amplified spontaneous emission (ASE) noise, as well as polarization controlled. We perform this implementation core by core in the experiment for all cores while all signals keep running. Subsequently, the filtered optical signal is coupled with a LO light centered at 1553.89 nm from the ECL2 ($<$100 kHz linewidth) by an optical coupler. The output optical signal from the coupler passes through the PC4 and a polarizer to align the polarization to maximize the responsivity of a broadband UTC-PD (NTT Electronics Corp. IOD-PMJ-13001). A polarization maintaining variable attenuator (VOA) is employed to adjust the input optical power of UTC-PD. Later, the combined optical signals are fed into the UTC-PD to generate THz signals, whose carrier frequency is determined by the frequency difference between two optical carriers of ECL1 and ECL2.

Fig. 3(b) depicts the optical spectra at the input of the UTC-PD. The center wavelengths of modulated and unmodulated laser beams are 1550 nm and 1553.89 nm, respectively, with

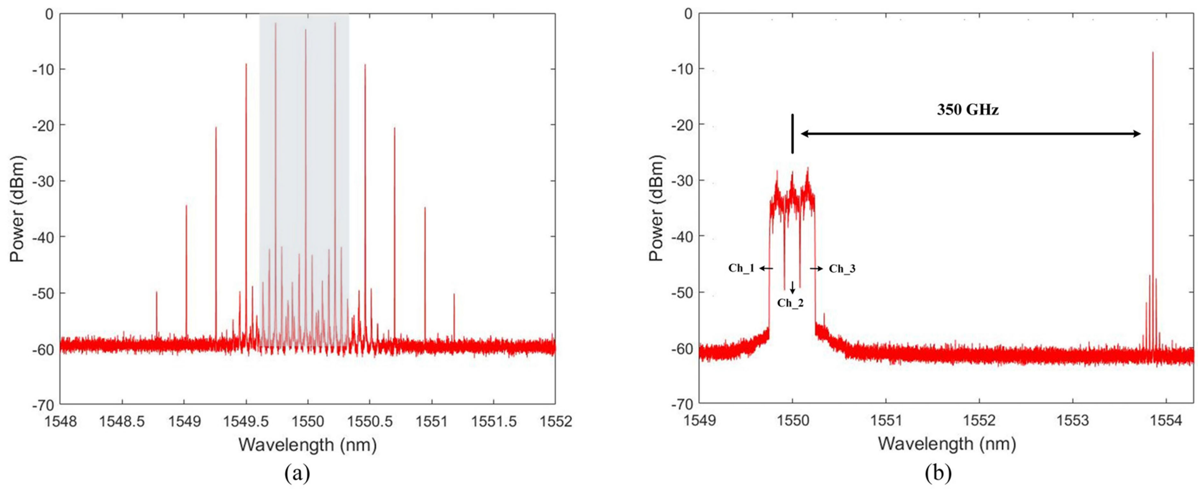

Fig. 3. (a) Optical spectra of optical frequency comb after the PM. (b) Optical spectra at the input of the UTC-PD.

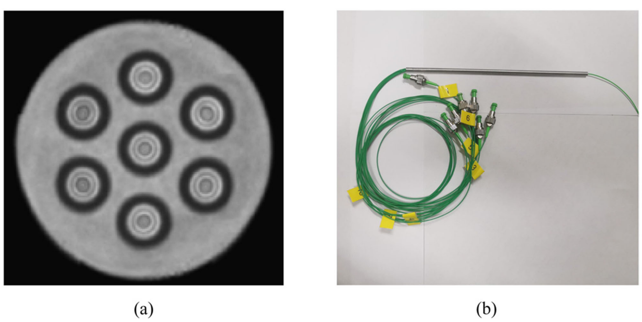

Fig. 4. (a) The cross-section view of the 1 km 7-core fiber. (b) The fabricated fan-in/fan-out modules.

a frequency difference of 350 GHz. The modulated optical path consists of three wavelengths with an equal spacing of 15 GHz. When two laser beams are fed into the UTC-PD and photo-mixed, three signals with corresponding different frequencies in the THz region are generated, the frequency of which are located at 365 GHz, 350 GHz and 335 GHz, respectively, named channel_1 (Ch_1), channel_2 (Ch_2) and channel_3 (Ch_3), respectively. Afterwards, the THz signals from the UTC-PD are radiated into a 10 m line-of-sight (LOS) wireless link via a horn antenna. Within the free space, a pair of THz lenses with 25 dBi gain are employed to collimate the THz beam to reduce the propagation path loss.

At the receiver side, a Schottky mixer driven by a 12-order frequency multiplied electrical LO signal is used to down-convert the received THz signals into the intermediate frequency (IF) domain. The LO signal is generated from an analog signal generator (Keysight, E8257D), the frequency and amplitude of which are at 372.5 GHz and 0 dBm, respectively. After mixing with the LO signal, three IF signals centered at 7.5 GHz, 22.5 GHz and 37.5 GHz are generated. Subsequently, the IF signals are amplified by an electrical amplifier (RFA4) with 22 dB gain, and then sampled by a real-time digital storage oscilloscope (DSO, Keysight, DSOZ594A) with 160 GSa/s sampling rates. Finally, the three IF signals are demodulated separately through offline DSP algorithms in the digital domain.

B. Digital Signal Processing (DSP) Routine

At the transmitter side, a pseudo-random binary sequence (PRBS) with a word length of 2^{15}-1 is used as the user data. Then, the 16-QAM modulation and pulse shaping are employed to generate the transmitted samples. Here a squared root raised cosine (SRRC) function is used for pulse shaping. At the receiver side, the received signal is first down-converted to the baseband with a digital mixer, which consists of a digital down-converter, a digital current block and a low-pass filter [16]. Then, the IQ imbalance of the baseband signal is compensated with Gram-Schmidt algorithm [17]. After this, a time recovery algorithm, which consists of the Gardner resampling and decimator, is used to resample the signal to the original baud rate. Following the time recovery, a linear equalization is employed based on Multi-Modulus-Algorithm (MMA) [18]. Then the frequency offset is compensated by Viterbi & Viterbi algorithm [19] and the phase noise is compensated by a blind phase search method [20]. Finally, the error vector magnitude (EVM) performance between the received signals and the baseband signals is evaluated, and the bit-error-rate (BER) performance is then estimated based on it [21][22]. In our experiment, the threshold of SD-FEC with 20% overhead is 2.7×10^{-2}, and the threshold of HD-FEC with 7% overhead is 4.5×10^{-3}. The parameter optimization in DSP routine is shown in Fig. 5.

The optimization of DSP algorithms is performed step by step following the DSP routine in the digital domain. The bandwidth of a low-pass filter is firstly optimized in terms of transmission BER performance. In the case of 14 Gbaud, a bandwidth of 14.7 GHz filter ensures the best performance, as shown in Fig. 5(a). After this, we optimize the tap number of the linear equalization to 70, as shown in Fig. 5(b). Subsequently, the iteration number of the linear equalizer and the phase angle resolution of phase noise compensator are also optimized, as shown in Fig. 5(c) and Fig. 5(d). As the number of iterations

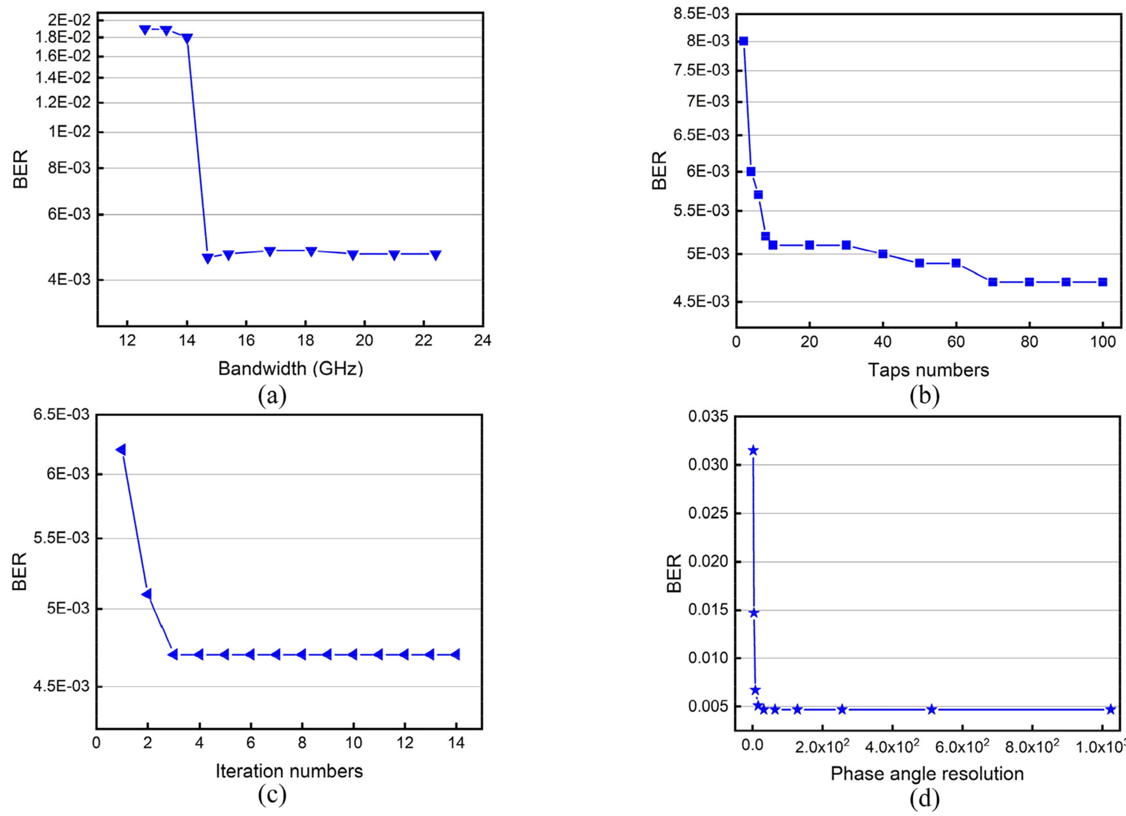

Fig. 5. The optimization of parameters in digital signal processing. (a) Bandwidth optimization of low-pass filter, (b) optimization of number of linear equalization taps, (c) optimization of linear equalizer iterations, (d) optimization of phase angle resolution.

increases and the phase angle resolution decreases, the BER performance becomes better. However, the BER performance is basically stable when the number of iteration exceeds 3 and the phase angle resolution less than 0.0245 rad. When the number of iterations further increases and the phase angle resolution is further reduced, the complexity of the algorithm and the computing time increases significantly. By considering this trade-off, the iteration number and phase angle resolution are set as 3 and 0.0245 rad, respectively.

III. Experimental Results and Discussions

A. BER Versus Optical Power

In the experiment, all 7-core duplicate the optical signals. Three-wavelength is all modulated by 16-QAM baseband for each core transmission. Fig. 6 presents the measured BER performance of overall 21 channels after 1 km 7-core fiber and 10 m wireless transmission. The baud rates are set to 14 Gbaud. From the Fig. 5, we can observe that the BER performance of each individual channel becomes better as the optical power increases, and for the same channel within different cores, the BER performance is constant forming a cluster with ignorable penalty. All the BER performance of 21 channels can reach below the soft decision forward-error-correction (SD-FEC) threshold with 20% overhead [23]. In particular, the BER performance of for Ch_1 and Ch_2 in all cores can reach below the hard decision forward-error-correction (HD-FEC) threshold with 7% overhead [24], [25]. In this case, each core carries a data rate of

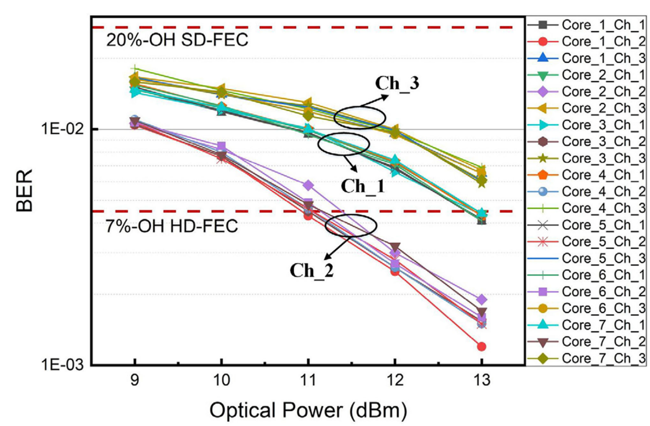

Fig. 6. The measured BER performance of overall 21 channels after 7-core fiber and 10 m wireless transmission.

14 Gbaud × 4 bit/s/Hz × 3 channels = 168 Gbit/s, resulting an aggregate line data rate of 1176 Gbit/s (168 Gbit/s × 7) in the 7-core fiber. Taking into account the error-correction overhead, a net data rate of 1059 Gbit/s after hybrid fiber wireless transmission is achieved. We can observe that the BER performance of the Ch_1 is worse than that of the Ch_2, which is mainly caused by frequency-dependent noise figure of IF amplifier (RFA4) and correlative interference from neighbor channels. Besides, due to the limitation of the Schottky mixer (∼40 GHz IF bandwidth), the Ch_3 with modulation exceeds the 3 dB bandwidth range.

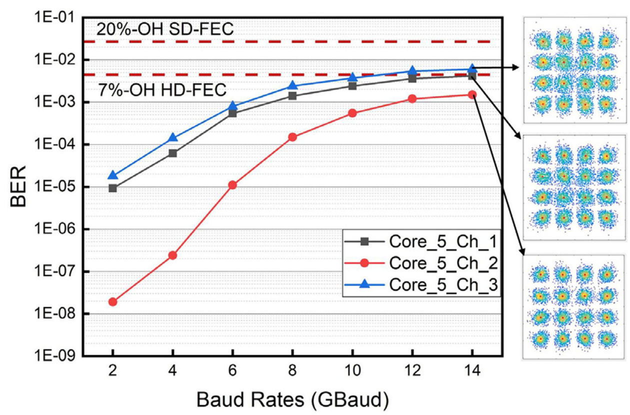

Fig. 7. The measured 3-channel BER performance of core_5 versus baud rates when the optical power is 13 dBm.

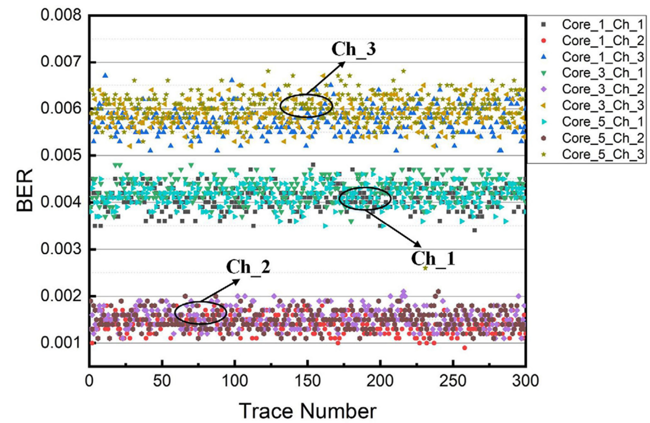

Fig. 8. System stability of 3-channel in core_1, core_3 and core_5.

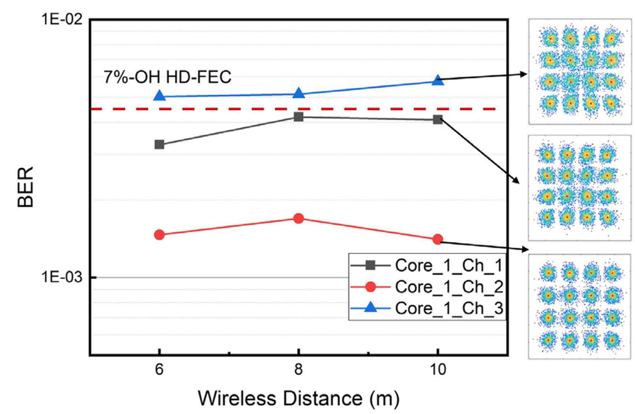

Fig. 9. The measured wireless distance dependent BER performance of 3-channel in core_1.

Consequently, the SNR of Ch_3 degrades dramatically, and it is with the worst performance.

B. BER Versus Baud Rates

In the experiment, we also demonstrate 16-QAM THz wireless transmission at different baud rates. The optical power launched into the UTC-PD is 13 dBm. The measured BER performance of the core_5 for 3-channel, as an example, is depicted in Fig. 7 with baud rates of 2 Gbaud, 4 Gbaud, 6 Gbaud, 8 Gbaud, 10 Gbaud, 12 Gbaud and 14 Gbaud. When the baud rates are 14 Gbaud, the constellation of 3 channels in core_5 is shown on the right side of Fig. 7 and the BER values for 3 channels are 4.2×10^{-3}, 1.5×10^{-3} and 6×10^{-3}, respectively. From the Fig. 7, we can see that the BER performance becomes worse as the baud rate increases, this is due to the reduction of electrical SNR in the case of fixed power, as well as less guardband between neighbor channels. When the baud rates are lower than 10 Gbaud, the BER performance of all 3-channel can reach below the HD-FEC.

C. System Stability Test

In addition, we evaluate the stability of BER performance in THz wireless communication link at the highest baud rates (14 Gbaud) in the lab environment. The optical power is set to 13 dBm. Fig. 8 shows the measured results for selective 3 channels - core_1, core_3 and core_5. For each channel of core_1, core_3 and core_5, we run the link continuously over 1 hour, collecting 300 traces per channel and recording the value of BER. From the Fig. 8, the BER performance of each channel in core_1, core_3 and core_5 is maintained within a small fluctuation range. We also see that 3 channels individually possess stable performance forming a cluster over 300 measured traces, while features different performance channel by channel, as observed in Fig. 6. The measured results indicate that the THz wireless communication systems can operate stably with data rates exceeding Tbit/s over a long time.

D. BER Versus Wireless Distance

Finally, we measure the BER performance at different wireless distances as well. The optical power and band rates are set to 13 dBm and 14 Gbaud, respectively in the experiment. Fig. 9 shows the measured BER performance of 3 channels over core_1, as an example, and wireless transmission distance of 6 m, 8 m, 10 m, respectively. When the wireless distance is 10 m, the constellation of 3 channels in core_1 is shown on the right side of Fig. 9 and the BER values for 3 channels are 4.1×10^{-3}, 1.4×10^{-3} and 5.7×10^{-3}, respectively. From the Fig. 9, we can see the BER performance slightly degrades as the wireless transmission distance increases from 6 m to 8 m. Meanwhile, the BER performance variation can be also observed when distance further increases to 10 m. This is mainly caused by the alignment accuracy variation of the THz transmitter and receiver.

IV. Conclusion

In summary, we propose and experimentally demonstrate a multi-dimensional multiplexing THz-over-Fiber wireless communication system targeting an extremely large capacity of Tbit/s. Based on the combination of the OFC for WDM, the multi-core fiber for SDM, spectrally efficient modulation format for amplitude and phase multiplexing, as well as the advanced

DSP algorithm, successful hybrid transmission of a line data rate of up to 1176 Gbit/s over 1 km fiber and a wireless distance of 10 m in the 350 GHz is achieved. Amongst 3 FDM channels, the BER of one after transmission is below the SD-FEC and two is below the the HD-FEC thresholds, resulting in a net data rate of 1059 Gbit/s. This is the largest capacity ever-reported in the THz region above 300 GHz, to our best knowledge. The proposed THz communication system is expected to pave the way towards the evolution for Tbit/s wireless communication, and boost the evolution and implementation of the 6G wireless communication networks.

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