Demonstration of 60 Gbps 135 GHz Terahertz Signal Transmission over 4600-m Wireless Distance with Photonics-aided Technology

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***Abstract*— We experimentally demonstrate that 135 GHz 60 Gbps QPSK signal is successfully transmitted over a wireless distance of 4600 m, and the BER of the transmitted signal is less than 20% SD-FEC threshold of 2.4×10^{-2}.**

Keywords—photon-assisted, terahertz, quadrature phase shift keying (QPSK), long wireless transmission

I. Introduction

The terahertz (THz) band refers to the region of the electromagnetic spectrum between millimeter waves and infrared optics in the frequency range of 0.1-10 THz. Because it has a huge unallocated bandwidth and can support data transmission rates above 10 Gbps, the use of terahertz bands for communication can effectively alleviate the increasingly tight spectrum resources and the capacity limitations of current wireless systems, and is the primary choice for future wireless communications. Among them, the sub-THz band (100 – 300 GHz) is the expected frequency band that can be used for long-distance high-speed mobile data communication, because this band can have wider bandwidth while maintaining relatively low atmospheric attenuation. Fig. 1 shows a series of experimental results of sub-THz wave signal transmission at 110-150 GHz. In 2010, NTT reported a D-band wireless transmission system with a wireless distance of 5.8 km and the data rate of 10.3 Gbps at 120 GHz. The system uses the amplitude shift keying (ASK) modulation format, and the maximum distance-rate product is 10 Gbps×5.8 km = 58 Gbps·km [1]. Reference [2] proved that the 140 GHz 10 Gbps 16-ary quadrature amplitude modulation (16QAM) can be transmitted over a 1.5 km wireless link by using all-solid-state electronic hybrid technology, but the maximum distance-rate product is only 10 Gbps×1.5 km = 15 Gbps·km. In 2017, a real-time wireless communication system with a range of 21 km and a bit rate of 5 Gbps was established at 140 GHz [3]. Compared with the all-electric technology, the photon-assisted THz transmission system can effectively overcome the bandwidth limitation of commercial electronic components, while facilitating the seamless integration of wireless and fiber networks. Based on the technique of photonics-aided heterodyne beating, reference [4] has demonstrated the wireless transmission of 56 Gbps 8-ary pulse amplitude modulation (PAM 8) signals at 135 GHz over 3 m. Reference [5] has demonstrated 328 Gbps polarization-division-multiplexing 16-ary quadrature amplitude modulation (PDM-16QAM) indoor wireless transmission over 0.4 meters. Reference [6] has achieved 153.3 Gbps polarization-division-multiplexing quadrature phase shift keying (PDM-QPSK) signal transmission over a wireless

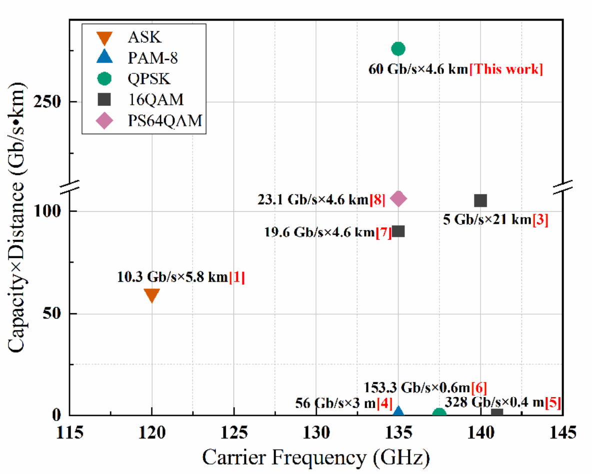

Fig. 1. Experimental demonstration of wireless transmission signals in the sub-THz band

distance of 0.6 m. Although the data rate exceeds 100 Gbps, the wireless distance is far from meeting the practical application requirements. Recently, we achieved 19.64 Gbps signal transmission [7] and 23.1 Gbps quadrature phase shift keying (QPSK) signal [8] over a 4.6 km wireless link. In this paper's work, we achieve the currently largest distance-rate product at 135 GHz.

In the paper, we experimentally demonstrated the transmission of 135 GHz 40/60 Gbps QPSK signals over 4600 m wireless links using only traditional low-complexity DSP at the transmitter and receiver ends , the results show that the bit error rate (BER) of 40 Gbps (20 Gbaud) QPSK signal after wireless transmission is less than 7% hard-decision forward error correction (HD-FEC) threshold 3.8×10^{-3}, BER of 60 Gbps (30 Gbaud) QPSK signal is less than 20% soft-decision forward error correction (SD-FEC) threshold of 2.4×10^{-2}. In addition, we also studied the BER performance of 40 Gbps QPSK signals in the 135-150 GHz THz band, and successfully realized the transmission of 40 Gbps QPSK signals in the highest frequency band of 145 GHz, with BER below the 20% SD-FEC threshold of 2.4×10^{-2}. As far as we know, this is the first time that the transmission of QPSK signal up to 60 Gbps at 135 GHz has been achieved in a long-distance wireless link of 4600 m.

II. Experimental Setup

Fig. 2 shows the experimental setup for photonics-aided THz signal transmission over a 4600 m wireless link. At the transmitter side, two free-running external cavity lasers (ECL1 and ECL2) with less than 100 kHz linewidth are used to generate THz signals. The ECL2 at 1550 nm acts as an optical local oscillator (LO) not used for modulation. The ECL1 at the center wavelength of 1551.04 nm is used as an optical carrier source and is launched into an in-phase/quadrature modulator (I/Q mod.). The baseband QPSK signals are generated off-line by MATLAB software in the digital domain. First, the PRBS sequence is format-modulated to generate QPSK signal, then double up-sampled and RRC filtered, and finally resampled to the sampling rate of the arbitrary wave generator (AWG). The signal is then converted to analog by uploading it to an AWG sampling rate at 120 Gsa/s. The signal from the AWG is boosted by two parallel electrical amplifiers (EAs) and sent to the I/Q mod. with a 3 dB bandwidth of 30 GHz for modulation. A polarization-maintaining Erbium-doped fiber amplifier (PM-EDFA) is inserted between the I/Q mod. and the polarization-maintaining optical coupler (PM-OC) to amplify the modulated optical signal. Then the modulated signal is coupled with the optical LO signal generated by ECL2, and the frequency space between the two signals is 135 GHz. After the coupled signal is transmitted over 100 m SMF-28, an attenuator (ATT) is used to adjust the optical power into uni-traveling-carrier photodiode (UTC-PD). Here, the UTC-PD with an operating frequency range of 110 - 170 GHz is used, and the optical signal is injected into the UTC-PD to obtain THz signal. It is worth noting that the part of the experimental setup before the 100m SMF-28 transmission was placed in a room at a certain distance from the transmitter. The generated 135 GHz wireless signal is amplified by a low-noise amplifier (LNA1, 110-170 GHz) with a gain of 18 dB and a power amplifier (PA, 110-150 GHz) with a saturated output power of 14 dBm. The signal is then sent into free space through a transmitter horn antenna (HA1) with 25 dBi gain. In the wireless link, we deploy a pair of lenses (Lens1 and Lens2) in front of the transmitter and receiver antennas to focus and collimate the THz wireless signal to support a 4600 m long-distance wireless transmission. The diameters of Lens1 and Lens2 are 10 cm

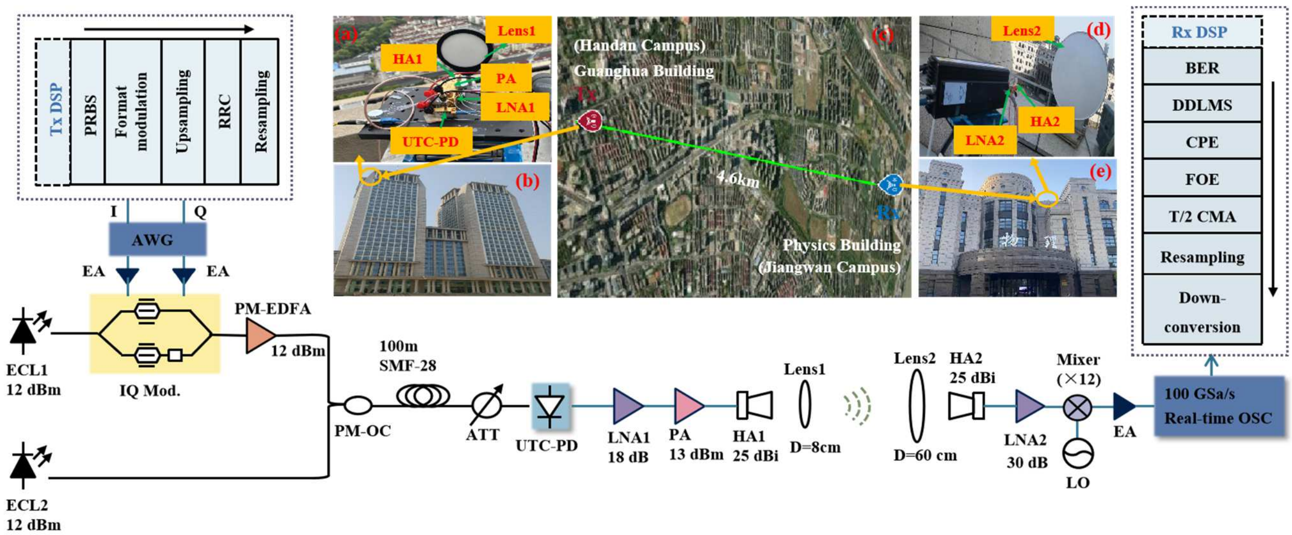

Fig.2. The experimental setup for photonics-aided THz signal transmission over 4600 m wireless distance. (a) Transmitter picture; (b) Transmitter side Guanghua building picture; (c) Transmission link; (d) Receiver picture; (e) Receiver side Physics building.

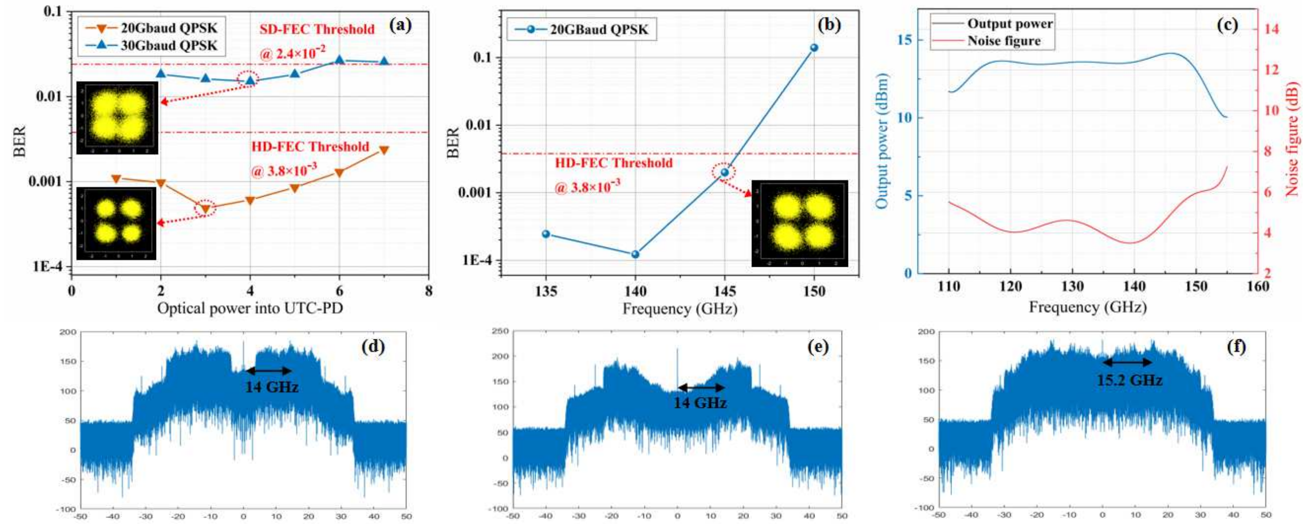

Fig.3. (a) The BER performance of QPSK signal versus the optical power into UTC-PD. (b) BER Performance versus carrier frequency for 20Gbaud QPSK signal; (c) When the input power is -5dBm, the output power and noise figure curve of PA. When the optical power entering the PD is 3 dBm, (d) 20 GBaud QPSK signal spectrum at 135GHz; (e) 20 GBaud QPSK signal spectrum at 150GHz; (f) 30 GBaud QPSK signal spectrum at 135GHz.

and 60 cm, respectively. Among them, the wireless transmitter is located on the top floor of the Guanghua Building on the Handan Campus of Fudan University, with a height of 142 m, and the wireless receiver is located on the top floor of the Physics Building on the Jiangwan Campus of Fudan University, which is 24 m high. Fig. 2(a)-(e) shows the pictures of the transmitter side, the transmission link and the receiver side, respectively.

TABLE I. POWER BUDGET FOR WIRELESS LINK

Parameter	Value
P_T	13 dBm
G_T	40 dBi
$FSPL$	148.3 dB
G_R	58 dBi
L_m	4.5dB
P_R	-42.8 dBm

We estimate the received power P_R for a given power P_T at the transmitter. The wireless link power budget is calculated by using the Friis formula [9]:

$$P_R = P_T + G_T + G_R - FSPL - L_m \tag{1}$$

$$FSPL = 20\log\left(4\pi df/\mathrm{c}\right) \tag{2}$$

Where P_T presents the transmit power, G_T represents the combined gain of the transmitter antenna HA1 and Lens1, G_R represents the combined gain of the receiver antenna HA2 and Lens2, $FSPL$ represents the free space path loss, L_m represents the atmospheric loss, and d is the wireless transmission distance, f_0 is the carrier frequency and c is the speed of light in vacuum. Table I lists the power budget for the wireless link of our experimental system. The typical output power of the PA is 13 dBm (P_T) at 135 GHz. G_T and G_R are about 40 and 58 dBi respectively. $FSPL$ equals 148.26 dB. The L_m for a 4.6 km wireless range link is about 4.5 dB at 135 GHz on a clear day [10]. As a result, our estimated power P_R was received equal to -41.8 dBm. Taking into account the additional connection loss between devices, this predicted received power is close to our measurement result of -43.2dBm.

At the wireless receiver side, the received wireless signal is first amplified by LNA2 with a gain of 30 dB, and then in the analog domain, it is down-converted to an intermediate frequency (IF) signal after being mixed with the 12-multiplied RF LO from the 12.1 GHz by a mixer. Therefore, the IF carrier frequency is about 15.2 GHz (12.1 GHz × 12 - 135 GHz). After being enhanced by EA, the IF signal is converted and sampled by a digital storage oscilloscope (OSC). The deployed OSC has a sampling rate of 100 GSa/s and a 3-dB bandwidth of 33 GHz. Finally, the IF signal captured by the OSC is processed in MATLAB for offline digital signal processing (DSP). We use a low-complexity traditional DSP at the receiving end to restore the signal. The specific Rx offline DSP process includes: down conversion, resampling, T/2 constant modulus algorithm (CMA) equalization with 51-taps, frequency offset estimation (FOE), carrier phase recovery (CPR) and 31-taps T spaced direct-detection least mean square (DD-LMS) equalization. Specifically, the processes of transmitter DSP (Tx DSP) and receiver DSP (Rx DSP) are shown in Fig. 2.

III. EXPERIMENTAL RESULT

In the experiment, we transmitted 135 GHz 40 Gbps (20 Gbaud) and 60 Gbps (30 Gbaud) QPSK signals over a wireless distance of 4600 m, and down-converted them to IF signals at 14 and 15.2 GHz, respectively. The spectra of 20 and 30 Gbaud IF QPSK signals captured by the OSC are shown in Fig. 3(d) and (f), respectively. Fig. 3(a) shows the BER and optical power curves of the input UTC-PD power for 20 and 30 Gbaud QPSK signals. The BER after wireless transmission of 20 Gbaud QPSK signal for 4600 m is less than the HD-FEC threshold of 3.8×10^{-3} with an overhead of 7%. And the BER of 30 Gbaud QPSK signal is less than the 20% SD-FEC threshold of 2.4×10^{-2}. In the 4600m 135GHz THz wireless transmission system, a maximum transmission rate of 60 Gbps can be achieved.

In addition, we also studied the BER performance of 20 Gbaud QPSK signal after wireless transmission of 4600m in different THz frequency bands of 135-150 GHz. We set the optical power entering the PD at the best performance point of 3 dBm, and the curve of BER changing with the signal frequency band is shown in Fig. 3(b). When the frequency of THz waves increases from 135 GHz to 150 GHz, the performance of 20 Gbaud QPSK signals generally shows a downward trend. When the transmission frequency band is lower than 145 GHz, the 20% SD-FEC threshold of 2.4×10^{-2} can be satisfied. Fig. 3(c) shows the carrier frequency versus output power and noise figure of the transmitter PA. As shown in Fig. 3(d) and Fig. 3(e), compared to 135 GHz, the signal fading is more serious in the received signal spectrum at 150 GHz. At this time, because the high-frequency part of the signal deviates from the optimal response range of the PA and the RF line, the high-frequency part is almost submerged by noise.

IV. Conclusion

We experimentally demonstrate that 30 Gbaud QPSK signal can be transmitted over a wireless distance of 4600 m in a photonics-aided THz transmission system. The total rate reaches 60 Gbps, and the BER is less than the 20% SD-FEC threshold of 2.4×10^{-2}, achieving a record of wireless transmission distance-rate product up to 276 Gbps·km (60 Gbps×4.6 km) at 135 GHz. In addition, the transmission of 40 Gbps QPSK signal in higher frequency bands in this transmission system has been further explored. The BER of 145 GHz 40 Gbps QPSK signal is less than the 20% SD-FEC threshold of 2.4×10^{-2} after 4600 m wireless transmission. The experiments fully verified the potential of photonics-aided THz technology in future large-capacity and long-distance wireless transmission.

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