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Experimental demonstration of 220-GHz terahertz signals wireless transmission over 4.6 km

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The advancement of terahertz (THz) communication technology drives the evolution of wireless communication systems, offering novel pathways and technical means for the development of future 6G communication systems. Traditional wireless communication systems are often constrained by bandwidth limitations of electronic devices in high frequency bands. However, THz communication technology leverages the characteristics of electromagnetic waves to transcend these limitations, enabling communication at higher frequencies and wider bandwidths. Among these, the 100–300 GHz (sub-)THz frequency range stands out due to its relatively low atmospheric attenuation and ample system bandwidth, making it more suitable for establishing long distance point-to-point wireless links. Especially for long-distance transmission in high-frequency bands, the 220-GHz band has emerged as a new research hotspot for wireless transmission. Currently, 220-GHz frequency band wireless links are mainly classified into three categories: all-electronic, photonic-electronic, and all-optical systems. In all-electronic systems, THz signals are generated using electronic frequency multipliers at the transmitter and down-converted using electronic mixers at the receiver. For example, Boes et al. [1] achieved a transmission rate of 96 Gbps at 240 GHz, with a transmission distance of 0.4 km. Guo et al. [2] accomplished a wireless transmission distance of 2.5 km and a transmission rate of 0.1 Gbps at 220 GHz. In all-optical systems, both the transmitter and receiver utilize electro-optic modulators to modulate electrical signals onto optical carriers, posing higher requirements on optical receivers. In contrast, photonics-aided photonic-electronic links employ electro-optic modulators for signal modulation at the transmitter and pure electronic receivers at the receiver, thus alleviating the stringent requirements on both electronic and photonic devices while facilitating the transmission of ultra-high-frequency and broadband signals. For example, Koenig et al. [3] and Fice et al. [4] achieved transmission rates of 75 and 100 Gbps at 237.5 and 220–280 GHz, respectively, but the transmission distances were only 40 and 70 cm, respectively. Therefore, our aim is to explore the transmission characteristics of 220-GHz (sub-)THz signals in long distance wireless links based on photonics-aided technology.

In the study, we experimentally demonstrate a long distance wireless transmission system for 220-GHz (sub-)THz signals based on photonics-aided technology. We successfully achieved 5000-Mbaud quadrature phase shift keying (QPSK) signal transmission over a 1.2-km wireless link, with a bit error rate (BER) meeting the 15% soft decision forward error correction (SD-FEC) overhead. Furthermore, we accomplish 500- and 1000-Mbaud QPSK signal transmission over a 4.6-km wireless link, with BERs meeting the 15% and 25% SD-FEC overhead, respectively. The maximum system transmission bit rate of 2000 Mbps is achieved in the 4.6-km wireless transmission link. To our knowledge, this groundbreaking achievement represents a record in wireless transmission distance of 220-GHz THz signals using photonics-aided technology.

Experiment setup. Figure 1(a) shows the experimental setup diagram for photonics-aided long distance transmission of 220-GHz THz signals. In the transmitter control system (CS), photonics-aided technology is crucial for generating high frequency THz signals and enabling photonic link transmission. This technology employs two independent lasers to emit optical signals, with one laser used to modulate the transmission signal. The modulated signal is coupled with the unmixed signal and directed to a photodetector (PD). In the PD, these two optical signals are mixed and are converted into a THz signal with a frequency equal to the difference between the two laser frequencies. We use an integrated photonic THz signal source (PTSS) to generate the two optical beating signals entering the PD. The PTSS, shown in Figure 1(a) as the TX CS section, comprises two

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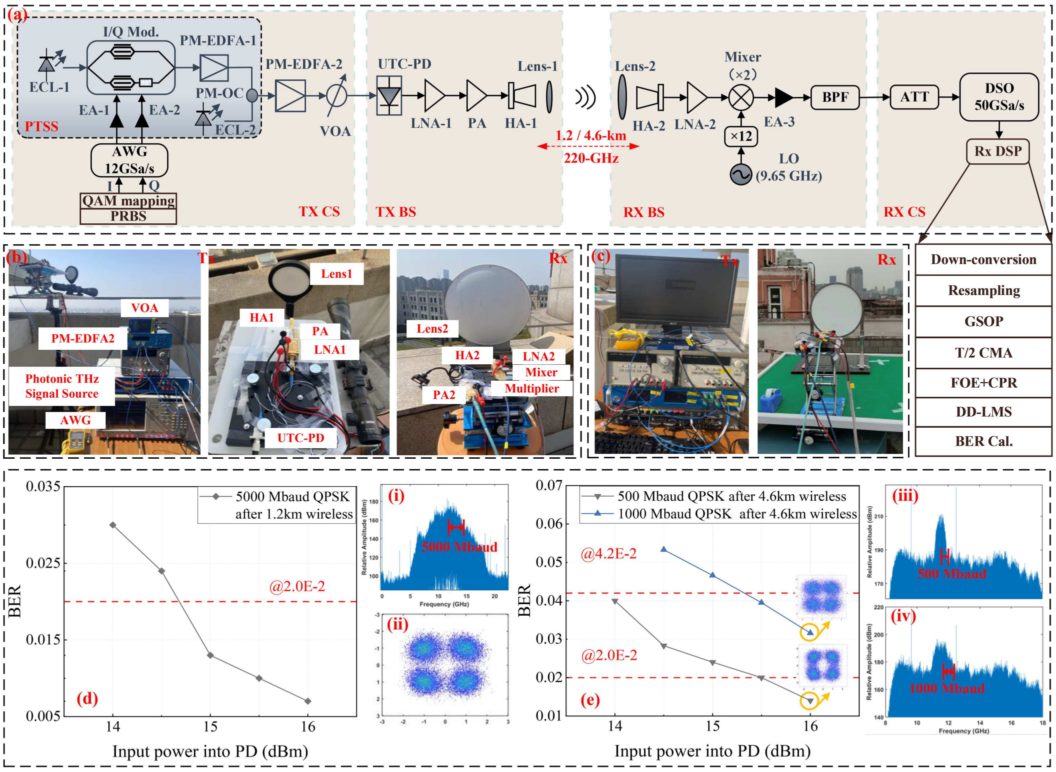

Figure 1 (Color online) (a) Experimental setup. (b) The transmitter and receiver images of the 4.6-km transmission link. (c) The transmitter and receiver images of the 1.2-km transmission link. (d) The BER curve of 5000-Mbaud QPSK signal over 1.2-km wireless transmission; (i) spectrum of the 5000-Mbaud QPSK and (ii) constellation diagram after DSP recovery at 16-dBm input UTC-PD power. (e) The BER curve of 500/1000-Mbaud QPSK signal over 4.6-km wireless transmission; spectra of (iii) 500-Mbaud and (iv) 1000-Mbaud QPSK signals at 16-dBm UTC-PD power.

external cavity lasers (ECLs) with a linewidth of 100 kHz each, a 30 GHz 3 dB bandwidth IQ modulator, two electrical amplifiers (EAs), a polarization-maintaining erbium-doped fiber amplifier (PM-EDFA), and a polarization-maintaining optical coupler (PM-OC). First, the 1550.00-nm continuous light wave emitted by the laser ECL-1 is incident on the IQ modulator to carry the baseband signal. The baseband signal is generated offline in MATLAB, mapped from a pseudorandom binary sequence (PRBS) to a QPSK signal, and then loaded into a 12-GSa/s arbitrary waveform generator (AWG) to generate analog signals with different baud rates. These signals are split into I and Q paths, fed into the PTSS, amplified separately by EA-1 and EA-2, and then input into the IQ modulator. The modulated optical signal is then amplified by PM-EDFA-1 and coupled with a 1551.76-nm optical carrier emitted by ECL-2 with a power of 13 dBm. The coupled output is achieved through the PM-OC. At the transmitter base station (BS), we generate and transmit THz wireless signals. The optical power of the signal entering the uni-traveling carrier photodiode (UTC-PD) is adjusted using a variable optical attenuator (VOA). The UTC-PD generates a 220-GHz THz signal through photomixing of the two optical beat signals. Due to the high free-space propagation losses in the (sub-)THz band, maintaining signal strength over long distances is critical. Selecting appropriate high-power amplifiers is essential to ensure sufficient power while avoiding saturation distortion. In this experiment, we use a low noise amplifier (LNA) and a power amplifier (PA) in series to amplify the wireless signal at the transmitter. Initially, LNA-1, with a frequency range of 210–260 GHz and a gain of 15 dB, provides preliminary amplification, followed by further amplification using a PA, which operates in the 195–225 GHz range with a saturated output power of 18 dBm. The amplified signal is transmitted to free space via a transmitting antenna (HA-1) with a 25-dBi gain. To maximize the received signal power, a pair of plano-convex lenses are used in both the 1.2 and 4.6 km transmission experiments to focus the THz beam. Lens-1 (10 cm diameter) and Lens-2 (60 cm diameter) are positioned at focal distances of 13 and 120 cm from the transmitting HA-1 and receiving HA-2, respectively, to ensure optimal signal focus. High magnification telescopes assist in aligning the transmitter and receiver. The transmitter is located on the rooftop of the Guanghua Tower at Fudan University's Handan campus in Shanghai, with the 1.2 km receiver on the rooftop of Building 25 at Wenhua Garden, and the 4.6 km receiver on the rooftop of the Physics Building at Fudan University's Jiangwan campus. The same transmitter and receiver devices are used in both transmission distances. The wireless transmission tests over 4.6 and 1.2 km are both conducted under clear sky and full terrestrial conditions.

We utilize the Friis transmission equation (1) [5] to compute the power budget in wireless communication systems.

$$P_R = P_T + G_T + G_R - 20\log(4\pi df/c). \tag{1}$$

In the experiment, we approximate the wireless transmit power P_T by the saturated output power of PA, which is 18 dBm. G_T represents the combined gain of the transmitter antennas HA-1 and Lens-1, approximately 40 dBi. G_R

denotes the combined gain of the receiver antennas HA-2 and Lens-2, which is 58 dBi. In the free-space transmission loss module, d denotes the wireless link distance, f represents the transmission frequency, and c denotes the speed of light in vacuum. According to theoretical calculations, the estimated received signal powers P_R at 1.2 and 4.6 km are approximately -24.87 and -36.54 dBm, respectively. However, in practice, due to factors such as air humidity and other environmental conditions, the actual received power is generally lower than the theoretical estimated value.

Therefore, at the receiver BS, we focus primarily on receiving and amplifying the THz wireless signal. Initially, the THz signal undergoes amplification by LNA-2, offering a 15-dB gain. Following this, the 9.65-GHz local oscillator (LO) undergoes a 12-fold multiplication before entering the mixer. Inside the mixer, it undergoes a two-fold amplification and then mixes with the THz signal, converting it to an intermediate frequency (IF) signal. Consequently, the IF carrier frequency is approximately 11.6 ($= 9.65 \times 24 - 220$) GHz. The IF signal is amplified by a bandpass amplifier, EA-3, with a gain of 50 dB and operating in the frequency range of 7–17 GHz. Finally, at the receiver CS, we conduct signal reception and offline digital signal processing (DSP). Then, the IF signal is captured by a digital storage oscilloscope (DSO) with a sampling rate of 50 GSa/s and a 3 dB bandwidth of 33 GHz after passing through a bandpass filter with a range of 9.5–13 GHz and a 20-dB attenuator. Figures 1(b) and (c) show the transmitter and receiver images of the 4.6-km and 1.2-km transmission systems, respectively. The captured IF signals are processed in MATLAB, including down-conversion, baseband resampling, and IQ imbalance correction using the Gram-Schmidt orthogonalization process (GSOP). Subsequently, a 51-tap T/2 constant modulus algorithm (CMA) compensates for channel interference, frequency offset estimation (FOE) corrects for laser frequency shifts, and carrier phase recovery (CPR) reduces phase noise. Finally, a 151-tap decision-directed least mean squares (DD-LMS) algorithm compensates for intersymbol interference (ISI). The DD-LMS equalization algorithm is an adaptive filtering technique that employs blind equalization, adjusting the filter weights based on the received signal to minimize the error between the received signal and a reference signal. The DD-LMS error function is

$$e(n) = d(n) - y(n), \tag{2}$$

where $d(n)$ is the reference signal, and $y(n)$ is the filter output. The filter weights are updated using gradient descent, with the weight iteration formula given by

$$\omega(n+1) = \omega(n) + \mu e(n) x(n), \tag{3}$$

where μ is the step-size parameter, and $x(n)$ is the input signal. Finally, the BER of these symbols is calculated.

Experiment results. Figures 1(d) and (e) illustrate the experimental results of long distance transmission of photonics-aided 220-GHz QPSK signals. In Figure 1(d), the variation of BER relative to the input optical power of the UTC-PD is depicted for the wireless transmission of a 5000-Mbaud QPSK signal over 1.2 km. We test input optical powers ranging from 14 to 16 dBm, with a 0.5 dBm increment, and observe a gradual reduction in signal BER with increasing optical power. At 16 dBm, we achieve a minimum BER of 7×10^{-3}, which meets the 15% SD-FEC threshold of 2.0×10^{-2}, and the maximum net bit rate reaches 8700 ($= 5000 \times 2/(1 + 15\%)$) Mbps. At this point, the spectrum of the IF signal captured by the DSO is shown in inset (i), revealing attenuation of high frequency signals due to the operation range of the receiver's bandpass amplifier and filter, which somewhat affects signal transmission efficiency. Meanwhile, the constellation diagram of the QPSK signal recovered by DSP is depicted in inset (ii).

Figure 1(e) presents the BER results of 500- and 1000-Mbaud QPSK signal transmission after 4.6 km. As the optical input power at the UTC-PD gradually increases, the signal-to-noise ratio (SNR) also increases, resulting in a gradual decrease in BER. At 16 dBm, we achieve a minimum BER of 1.4×10^{-2}, for the 500-Mbaud QPSK signal, meeting the 15% SD-FEC requirement. For the 1000-Mbaud QPSK signal, the BER at 16 dBm is less than 4.2×10^{-2}, satisfying the 25% SD-FEC threshold, and the maximum net bit rate reaches 1600 ($= 1000 \times 2/(1 + 25\%)$) Mbps. The spectra captured by the DSO after transmitting the 500- and 1000-Mbaud QPSK signals over 4.6 km appear in insets (iii) and (iv), respectively. The constellation diagrams after DSP recovery are shown in the insets of Figure 1(e). Thus, we have successfully achieved long-distance wireless transmission of 1600-Mbps QPSK signals in the 220-GHz frequency band, covering a distance of 4.6 km. To our knowledge, this sets a new record for wireless transmission distance of 220 GHz THz signals.

Conclusion. We establish a photonics-aided THz long distance wireless link, achieving a maximum net bit rate of 8700 Mbps for QPSK signals over 1.2 km and 1600 Mbps over 4.6 km. To the best of our knowledge, this study sets a record for 4.6-km wireless transmission in the 220-GHz band using photonics-aided technology. This demonstrates that the sub-THz band is suitable not only for short range high-bandwidth applications but also has the potential for medium and long range communication. This breakthrough lays the foundation for 6G networks and ultra-high speed communication systems.

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Supporting information Videos and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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