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104-GBaud/λ photonics-assisted fiber-wireless transmission system at 0.317-THz with digital subcarrier multiplexing

Jianyu LONG[1], Jianjun YU[1*], Xiongwei YANG[1], Ying WU[1], Ying WANG[1], Qinyi ZHANG[1], Yifan CHEN[1], Weiping LI[1], Kaihui WANG[1], Wen ZHOU[1], Chen JIANG[1], Shaozhi DENG[2*] & Ningsheng XU[3*]

[1]*State Key Laboratory of ASIC and System, Key Laboratory for Information Science of Electromagnetic Waves (MoE), School of Information Science and Technology, Fudan University, Shanghai 200433, China*
[2]*State Key Laboratory of Optoelectronic Materials and Technologies, School of Electronics and Information Technology, Sun Yat-sen University, Guangzhou 510275, China*
[3]*Nano Institute, Frontier Institute of Chip and System, Fudan University, Shanghai 200433, China*

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The advent of the 5G era and the forthcoming transition to 6G networks are driving increasing demand for high-capacity wireless transmission systems [1–5]. The terahertz (THz) band, spanning 0.3 to 10 THz, constitutes a vast and largely underutilized spectral resource, offering significant potential for future ultra-high-capacity wireless communications.

Photonics-assisted techniques for generating THz waves present considerable advantages over purely electronic methods, especially in producing ultra-broadband THz signals and enabling seamless integration with optical fiber infrastructure. These approaches also afford superior flexibility in tuning the THz frequency with notable operational simplicity. Although recent research has documented several photonics-assisted high-capacity THz transmission experiments [2–5] (Table 1), the achievable capacity of these systems remains limited and fails to fully leverage the extensive bandwidth available in the THz spectrum.

In broadband photonics-assisted THz transmission systems, the transmitter can utilize a uni-traveling-carrier photodiode (UTC-PD) to generate signals with ultra-wide bandwidth. However, at the receiver end, the bandwidth is often constrained by components such as mixers within the THz receiver. This limitation substantially restricts the potential increase in per-wavelength bandwidth for photonics-assisted THz links. To overcome these challenges, we propose to utilize digital subcarrier multiplexing (DSCM) [6], where each bandwidth-constrained receiver processes an individual subcarrier independently, thereby enabling the reception of ultra-wideband signals. This approach facilitates more effective utilization of the extensive bandwidth offered by photonics-assisted THz technologies.

In this study, a record-breaking 104-GBaud per wavelength fiber-wireless transmission system operating in the THz band is demonstrated, utilizing an ultra-wideband UTC-PD and DSCM technology. The system successfully transmits 2×52-GBaud probabilistically shaped (PS) 64-QAM DSCM signals over 25-km standard single-mode fiber (SSMF) and 1 m of wireless free-space link at 0.317 THz. To the best of our knowledge, this result achieves the highest symbol rate per wavelength (104-GBaud/λ) and the highest net data rate per wavelength per polarization (374.4 Gbps/λ/polarization) yet reported for a THz wireless system.

The ultra-wideband photonics-assisted THz transmission system spanning optical, THz, and wireless domains, is illustrated in Figure 1. At the transmitter side, an external cavity laser (ECL1) operating at 1550 nm with 100 kHz linewidth feeds a 40-GHz bandwidth IQ modulator, which is driven by 2×52-GBaud DSCM electrical signals generated from a 224-GSa/s arbitrary waveform generator (AWG). The digital processing chain preceding modulation includes PS-64-QAM mapping (PS-64-QAM-4.5; see [7]), root-raised-cosine filtering with a 0.01 roll-off factor, resampling to satisfy the AWG and DSCM requirements. As shown in Figure 1(b), the baseband 2×52-GBaud DSCM signal is configured with a 1 GHz guard band. The subcarrier bands 1 (B1) and 2 (B2) are allocated to the spectral bands [−53.02, −0.5] GHz and [0.5, 53.02] GHz, respectively.

Following modulation, the optical signal is amplified by a polarization-maintaining erbium-doped fiber amplifier (PM-EDFA), and transmitted via 25-km SSMF before another EDFA amplification. The amplified modulated optical signal is coupled with a second laser (ECL2 at 1552.536 nm) by a PM-OC, creating a 317-GHz frequency offset. The coupled signal is sent to a wide-band UTC-PD (IOD-PMJ-13001, 280–380 GHz, typical output power of −11 dBm), which generates the THz signal with a center frequency of 0.317 THz.

The wireless link incorporates specially designed horn antennas

* Corresponding author (email: jianjun@fudan.edu.cn, stsdsz@mail.sysu.edu.cn, xns@fudan.edu.cn)

Table 1 Remarkable achievements of high-speed broadband THz transmission (center frequency > 300 GHz).

Ref.	Center frequency (GHz)	Symbol rate /λ (GBaud)	Net rate /λ/Pol. (Gbps)	Modulation format	Spectral efficiency/Pol. (bps/Hz)	Wired+wireless distance
[2]	300	32	106.7	16-QAM	2.47	−+0.5 m
[3]	408	44.43	131.2	16-QAM	2.95	−+10.8 m
[4]	320	46	160	16-QAM	3.44	20 km+3 m
[5]	322	60	255	PS-64-QAM	4.21	20 km+3 m
This	317	104	374.4	DSCM PS-64-QAM	3.53	25 km+1 m

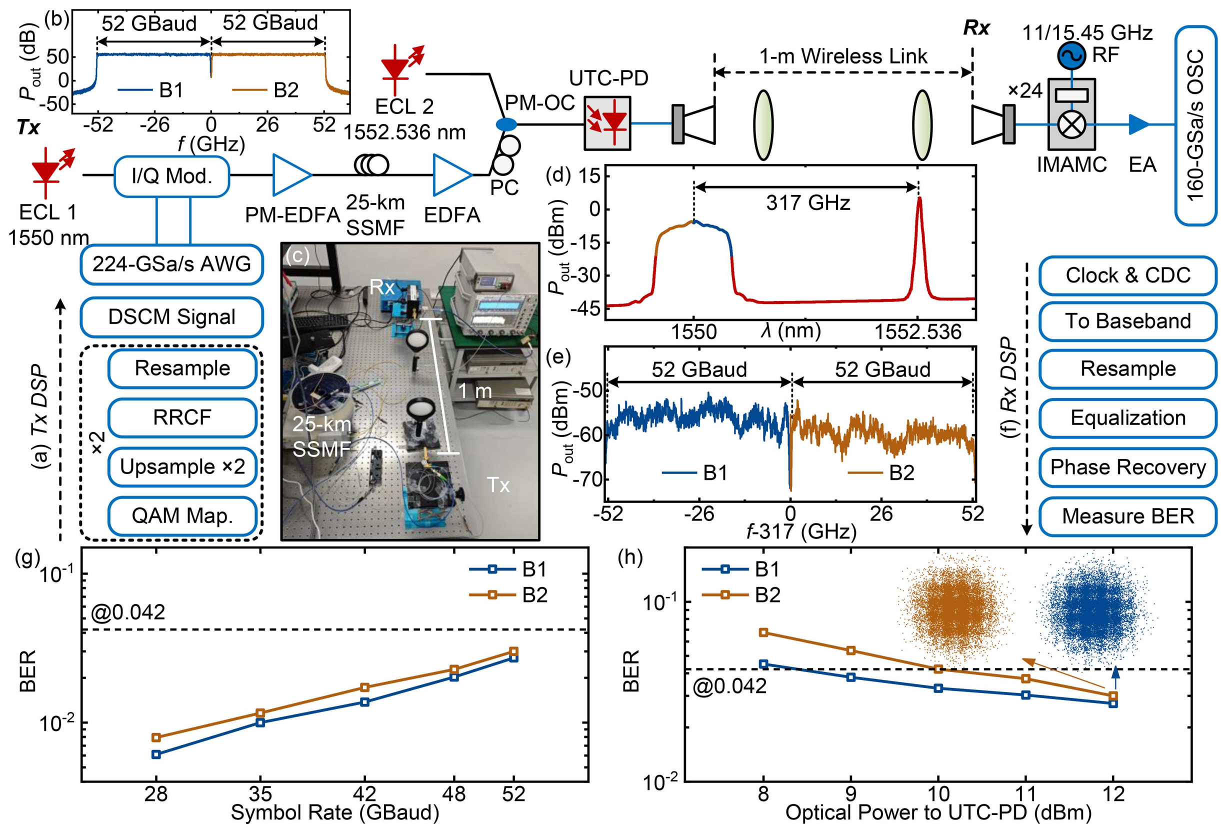

Figure 1 (Color online) Experimental setup diagram. (a) Tx DSP; (b) transmitted DSCM signal in Tx; (c) experimental photo; (d) optical spectrum fed to UTC-PD; (e) 104-GBaud signal spectra plotted from oscilloscope; (f) Rx DSP; (g) BER versus symbol rate; (h) BER versus optical power to UTC-PD. ECL: external cavity laser; AWG: arbitrary waveform generator; I/Q Mod.: I/Q modulator; PM: polarization-maintaining; EDFA: erbium-doped fiber amplifier; SSMF: standard single-mode fiber; PC: polarization controller; OC: optical coupler; UTC-PD: uni-traveling-carrier photodiode; RF: radio frequency source; IMAMC: integrated mixer/amplifier/multiplier chain; EA: electrical amplifier; OSC: oscilloscope.

(25 dBi) with a pair of lenses (Thorlabs, LAT200, poly tetra fluoroethylene, ∅10 cm, f = 20 cm, 15 dBi) to collimate the THz beams across 1-m free-space path. The combined gain of HA and Lens for Tx is 40 dBi, and for Rx is 40 dBi. At the Rx, an integrated mixer/amplifier/multiplier chain (IMAMC, C02.8DAS02, 260–400 GHz, IF bandwidth: 40 GHz) downconverts the 317-GHz signals to intermediate frequency using a ×24 frequency multiplication stage. A radio frequency (RF) source operating at 11.0 GHz or 15.45 GHz is used to receive the DSCM signal B1 or B2, respectively. An electrical amplifier (SHF 804, 21 dB) boosts the signals before digitization by a 160-GSa/s 63-GHz-bandwidth oscilloscope (OSC). Only one band of B1 and B2 is captured by OSC at a time. The 317-GHz center frequency was selected to balance the frequency-dependent response of the UTC-PD and IMAMC, ensuring the 104-GBaud signal remains within the optimal overlapping bandwidth of both devices.

In Rx DSP, the received signals first undergo clock recovery and chromatic dispersion compensation (CDC) for the 25-km SSMF before being down-converted to baseband and resampled to 2 samples per symbol (sps). After that, channel equalization and phase noise compensation are utilized, following the method described in [5]. Finally, the equalized signals are demodulated and evaluated through BER measurement after QAM demapping.

Figure 1(g) presents the bit error rate (BER) curves of the two subcarriers for the PS-64-QAM DSCM signal at different symbol rates, under optimized optical input power to the UTC-PD. The results indicate that the BER increases for both subcarriers as the symbol rate rises. Furthermore, subcarrier B2, located at a higher frequency, exhibits worse BER performance compared to subcarrier B1 at a lower frequency. This performance difference is attributed to the lower received flatness and amplitude observed for B2 in Figure 1(e), which likely contributes to its inferior BER relative to B1. Specifically, this degradation stems from the cumulative frequency-dependent attenuation of the bandwidth-limited IQ modulator, the UTC-PD, and the IF stage of the IMAMC.

Figure 1(h) shows the BER performance of the two subcarriers in the 2×52-GBaud PS-64-QAM DSCM signal (with an entropy of 4.5) under varying input power levels to the UTC-PD. It is observed that the BER decreases for both subcarriers as the input power increases. Again, subcarrier B2 demonstrates poorer BER performance than subcarrier B1. This configuration achieves a record-breaking signal bandwidth per wavelength of $2 \times 52 = 104$ GBaud/λ. Considering a 25% soft-decision forward error correction (SD-FEC) overhead, this also leads to a record net data rate per wavelength per polarization of $2 \times 52 \times 4.5/(1 + 25\%) = 374.4$ Gbps/λ/polarization. The DSCM scheme allows for further subcarrier division or the application of bit/power loading techniques to further enhance system performance.

We have demonstrated a record-breaking 104-GBaud per wavelength fiber-wireless transmission system in the THz band using an ultra-wideband UTC-PD and DSCM. We have successfully transmitted 2×52-GBaud PS-64-QAM DSCM signals over 25-km SSMF and 1-m wireless free-space link at 0.317 THz. To the best of our knowledge, this result achieves the highest symbol rate per wavelength (104-GBaud/λ) and the highest net data rate per wavelength per polarization (374.4 Gbps/λ/polarization) yet reported for a THz wireless system. This work establishes new performance benchmarks for photonics-assisted THz systems while paving the way for future ultra-high-capacity wireless networks.

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