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Photonics-assisted THz wireless transmission with air interface user rate of 1-Tbps at 330–500 GHz band

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Air interface user rate (AIUR) of 1-Tbps is one of the most important key performance indicators (KPIs) for the future 6G extreme connectivity [1]. Terahertz (THz, 300 GHz–10 THz) is recognized as a promising candidate technology in achieving the KPI towards Tbps. In the past few years, a series of THz wireless transmissions at record-high data rates including both the pure-electronic and photonics-assisted solutions have been demonstrated [2]. Pure-electronic transceivers at above 300 GHz have limited bandwidth resulting in the maximum AIUR not exceeding 100 Gbps. However, the photonics-assisted solutions have shown the superior characteristics of higher carrier frequency, wider adjusted range, and larger broad bandwidth with data rate beyond 100 Gbps. With the advanced digital signal processing (DSP), several large-capacity photonics-assisted THz wireless transmissions are demonstrated at above 300 GHz. At 339 GHz, single line 124.8 Gbps wireless delivery over 104 m distance is demonstrated with the aids of THz amplifier, high gain lens antenna, and probability shaping (PS)-256QAM modulation and equalization techniques [3]. At 408 GHz, the transmission of 157.46 Gbps over 10.7 m is realized using 16QAM-OFDM modulation and offline DSP including linear equalization, phase noise compensation, and nonlinear equalization (NLE) [4]. At 320–380 GHz, a line rate of 612.65 Gbps over 2.8 m wireless link is achieved using PS-64QAM-OFDM modulation, orthogonal polarization dual antenna, and post-equalization DSP [5]. However, to the best of our knowledge, the AIUR of 1-Tbps THz wireless transmission at 330–500 GHz band has not yet been reported. Traditional DSP equalization algorithms are sub-optimal for the high-order PS-QAM signals, and have hindered the development of the fiber-THz integrated system towards Tbps-level transmission capacity.

In this study, we have proposed an efficient vector-quantized variational autoencoder (VQ-VAE) framework with a classical complex-valued 2 × 2 MIMO equalizer, which can implement the polarization demultiplexing and nonlinear equalization, and also address the numerical instability and convergence issues for high-order PS-QAM modulation. Based on the above technique, we for the first time demonstrate a dual-channel 2 × 2 MIMO fiber-THz transmission system with a record AIUR of 1.0488 Tbps using 46 GBaud PS-64QAM modulation at 330–500 GHz band over 10 km fiber and 10 m wireless link without using THz power amplifier.

Experimental setup. The 1-Tbps fiber-THz 2 ×2 MIMO wireless transmission system enabled by photonics is shown in Figure 1. The electrical baseband signal is generated from a 92 Gsa/s arbitrary waveform generator (AWG) with a 3 dB analog bandwidth of 32 GHz and 8-bit resolution. Two free-running tunable external cavity lasers (ECL-1 and ECL-2) operating at 193.47 and 193.565 THz are coupled to serve as the optical input of an I/Q modulator. Over 10 km standard single-mode fiber (SSMF), the ECL-3 operating at 193.1 THz as an optical local oscillator (LO) is coupled, and then amplified by an erbium-doped fiber amplifier (EDFA) to effectively drive UTC-PDs. The frequency space between Ch1, Ch2, and LO is fixed at 370 and 465 GHz, respectively. The X- and Y-polarization diversities are achieved through a polarization beam splitter (PBS) and then up-converted by UTC-PDs to THz-wave wireless signals of the Ch1 and Ch2. Two polarization controllers (PCs) are used to adjust the incident polarization state to maximize optical power into the two polarization-sensitive UTC-PDs [6]. Figure 1(d) shows a photo of the test-bed setup with 10 m 2 × 2 MIMO wireless transmission link. Two parallel THz-wave signals from the

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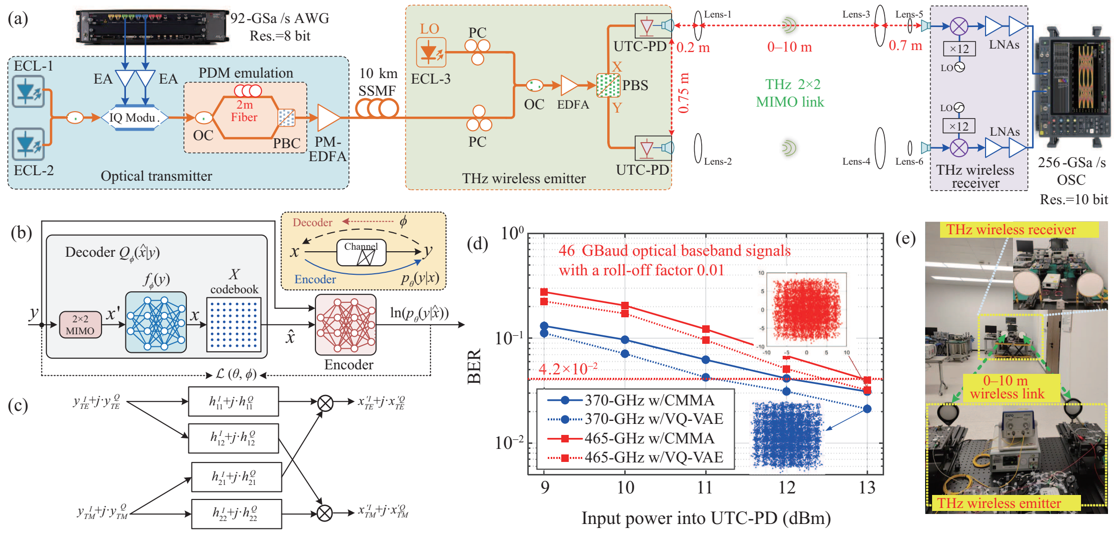

Figure 1 (Color online) (a) Experimental setup of 1-Tbps THz wireless transmission system. (b) Nonlinear compensation using VQ-VAE with (c) a classical 2 × 2 butterfly MIMO equalizer. (d) BER vs. input power with 46 GBaud PS-64QAM with CMMA and VQ-VAE equalizers at 370 and 465 GHz. (e) Photo of test-bed setup.

UTC-PDs are delivered over a 10 m 2 × 2 MIMO wireless link. Three pairs of manually-aligned lenses are deployed to maximize the received THz-wave signal power. Two same THz receivers working at 330–500 GHz band are driven by electronic LO sources to implement analog down conversion, and each has a mixer and a ×12 frequency multiplier chain. The intermediate frequency (IF) signal bandwidth of THz receivers can attain 40 GHz [7]. The LO sources for Ch1 and Ch2 are set to be 28.83 and 36.75 GHz, respectively. At the receiver, the IF signals are captured by a 256 GSa/s digital storage oscilloscope with 59 GHz bandwidth and 10-bit resolution for offline processing [2]. Note that, Ch1 and Ch2 are separately measured, but the total AIUR from the THz wireless transmitter is always constant at the Tbps-level. At the transmitter, a single carrier 46 GBaud PS-64QAM optical baseband signal with a roll-off factor of 0.01 is modulated by the AWG. The line rate corresponding to 46 GBaud 16QAM is 736 Gbps. Moreover, 46 GBaud PS-64QAM (5.7 bit/symbol) is measured, and the line rate is 46 GBaud × 5.7 bit/symbol/pol × 2 pol × 2λ = 1.0488 Tbps. We assume an ideal 25% SD-FEC threshold of 4.2×10^{-2} is used with a code rate of 4/5 [3]; hence the net rate is 46 GBaud × $(5.7-6\times(1-4/5))$ bits/symbol/pol × 2 pol × 2λ = 828 Gbps. At the receiver, an efficient VQ-VAE method with a classical 2 × 2 butterfly equalizer is proposed, which implements the polarization demultiplexing and equalization [6,8], as shown in Figures 1(a) and (b). Finally, the bit error rate (BER) can be calculated for the recovered signal.

Results and discussion. Based on the optimized parameters, we measure the BER versus input power into each UTC-PD over 10 km SSMF and 10 m wireless distance with 46 GBaud PS-64QAM with CMMA and VQ-VAE equalizers at 370 and 465 GHz, as shown in Figure 1(c). A record AIUR of 1.0488 Tbps and a net data rate of 828 Gbps can be achieved. The VQ-VAE method proposed in this study is more robust to variations in frequency space, modulation order, and learning rate, and can converge to a stable average BER performance under the threshold of 4.2 × 10^{-2}. Figure 1(d) shows a photo of the test-bed setup with 10 m 2 × 2 MIMO wireless transmission link. An efficient probability-aware VQ-VAE is used for the recovery of the high-order PS-QAM signals. This VQ-VAE equalizer exhibits better convergence properties and nonlinear equalization, which enables the fiber-THz integrated system to achieve Tbps-level THz wireless communication.

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Supporting information Appendixes A–D. 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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