

# Demonstration of record-high 352-Gbps terahertz wired transmission over hollow-core fiber at 325 GHz

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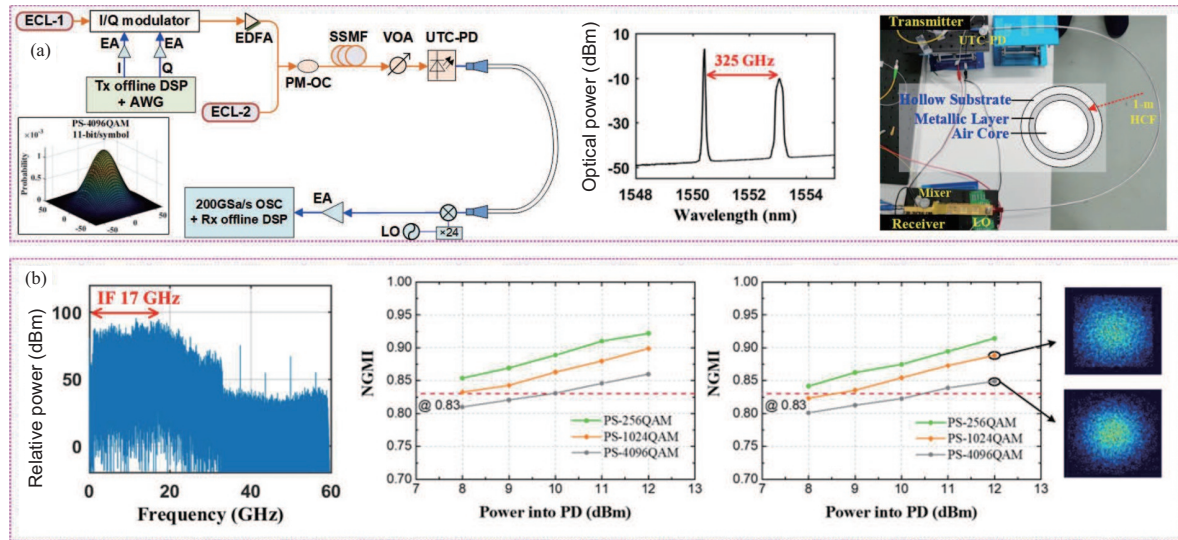
Terahertz (THz) waves, extending from 0.1 to 10 THz, are attracting extensive attention in the interdisciplinary fields of electronics and photonics. The THz band offers a larger available bandwidth, which can meet the Tbps transmission capacity for 6G wireless communication. Moreover, it could enable high-resolution sensing and imaging to implement Internet of Things (IoT) for trillion communicating devices, owing to the short wavelength compared to the microwave system [1]. However, the big obstacle of free-space THz wireless link is limited by the high atmospheric attenuation, and hence it just can be applicable to the line-of-sight transmission scenario. THz wired link based on specific fiber working at THz band has attractive features including light weight, low attenuation, flexibility, electromagnetic compatibility, and the capacity to support non-line-of-sight transmission [2]. Hence, the seamless integration transmission of THz wireless and wired links can leverage both approaches to expand THz practical application scenarios, which has great potential for future information and communication technologies.

**Research review.** The photonic-aided THz-wave communication scheme has been investigated to offer a variety of advantages over conventional all-electronic approaches. These advantages include wideband tunability of the wireless carrier frequency, large bandwidth, less harmonics, and seamless integration with optical transmission. Additionally, advanced multi-dimension multiplexing techniques in the optical domain such as wavelength/polarization division multiplexing (WDM/PDM), high-order modulation, can be used to realize broadband wireless transmission at line rates of 100 Gbps and beyond [3–5]. However, the photonics-assisted systems are still limited by the lower transmit power and the higher atmospheric attenuation in practical transmission. Integrating optical fibers, the transparent optical-THz-optical link is demonstrated to provide line-rates up to 240 and 190 Gbps over 5 and 115 m wireless distances at 230 GHz. Transparency is enabled by a plasmonic modulator which can map a THz signal directly onto an optical

carrier in an optical fiber [6]. Uncompressed high-definition 4K video (8 Gbps) transmission at 330 GHz has been successfully transmitted, as a proof of concept that the terahertz wireless link can directly interface with the terahertz optical fiber wired link [2]. The THz fiber is composed of an air-core region surrounded by a thin and low refractive index expanded polytetrafluoroethylene cladding layer, and the photonic-crystal waveguide is effectively designed for coupling THz fiber and wireless link. In W-band at 95 GHz, the 128 Gbps transmission has been demonstrated over two parallel spans of 1.5-m dielectric-coated metallic hollow fiber (DMHF) based on space division multiplexing [7]. The hollow-core fiber for efficient THz signal delivery could provide lower dispersion capabilities, lower loss, as well as the possibility to engineer wide bandgaps at higher frequencies [8].

**Experimental setup.** We have experimentally demonstrated the photonic-aided THz-wave wired communication system over 1-m hollow-core fiber (HCF) in (Figure 1(a)) [9]. To approach the Shannon limit of the THz channel, the probabilistically shaped quadrature amplitude modulation (PS-QAM) signal is generated by using the probabilistic amplitude shaping (PAS) scheme based on low density parity check (LDPC) encoder with 25% overhead (0.8 code rate). A tunable external cavity laser (ECL1) with 100-kHz linewidth as the optical carrier is modulated by an I/Q modulator with 30-GHz 3 dB bandwidth. Then, a cascaded erbium-doped fiber amplifier (EDFA) is used to amplify the modulated signals in order to compensate the insertion loss of the optics. Another laser ECL2 is applied as the optical local oscillator (LO), and the frequency space between the optical carrier ECL1 and optical LO ECL2 is 325 GHz. A polarization-maintaining optical coupler (PM-OC) is used to couple the two lasers. Subsequently, the uni-travelling carrier photodiodes (UTC-PD) generate the 325 GHz THz-wave signal and then transmit over 1-m THz HCF. Figure 1(a) shows the cross section of the HCF. In order to obtain flexibility, the hollow substrate of the THz HCF uses a polycarbonate

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**Figure 1** (Color online) (a) Experimental setup for 352-Gbit/s terahertz wired transmission over hollow-core fiber at 325 GHz; (b) NGMI of 32-Gbaud PS-256QAM, PS-1024QAM, and PS-4096QAM THz signals versus PD received power at BtB case and after 1-m HCF transmission, respectively. AWG, arbitrary waveform generator; DSP, digital signal processing; EA, electrical amplifier; SSMF, standard single mode fiber; VOA, variable optical attenuator; OSC, oscilloscope.

tube, which can be coiled and bent. The inner metal plating layer is formed from the silver film with 0.3  $\mu\text{m}$  thickness. The linear transmission loss of the THz HCF is 1.33 dB/m at 300 GHz, and the inner diameter is 3.6 mm [10]. At the receiver side, the received THz signals over 1-m HCF transmission are sampled by a real-time 200-GSa/s sampling rate oscilloscope with 59-GHz 3 dB bandwidth.

**Results and discussion.** The measured normalized generalized mutual information (NGMI) of 32-Gbaud PS-256QAM, PS-1024QAM, and PS-4096QAM signals versus PD received power at back-to-back (BtB) case and after 1-m HCF transmission are shown in Figure 1(b), respectively. At BtB case, the NGMI of PS-256QAM and PS-1024QAM signals are all above the 0.83-NGMI LDPC threshold. For PS-4096QAM signal, when the PD received power reaches 10 dBm, the post-FEC error free can be obtained. Moreover, there is around 0.5-dB power penalty after 1-m HCF transmission compared with the BtB case. For PS-4096QAM signal, the received power of the PD is improved to 10.5 dBm at the 0.83-NGMI LDPC threshold. For PS-1024QAM signal, the required power into PD is 8.6 dBm at 0.83-NGMI threshold. By using 32-Gbaud PS-4096 QAM signal, the record-high 352 Gbps single line rate (275.2-Gbps net data rate) of the THz wired transmission and 8.6 bit/s/Hz net spectrum efficiency is obtained at 0.83-NGMI threshold with 25% overhead. The deployed THz HCF has a wide wavelength range from visible light to far infrared and even THz band. Furthermore, the loss of the cladding modes propagating through the HCF is near to air loss window. The promising results show THz HCF paves the way for 6G THz wireless and wired link seamless integration network, enabling in-depth coverage of THz signal in indoor scenarios.

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