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Optical-terahertz-optical seamless integration system for dual-λ 400 GbE real-time transmission at 290 GHz and 340 GHz

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Terahertz band (THz-band, 0.3 to 10 THz) communications are envisioned as a promising candidate for 6G and beyond technology, which can provide data capacity tens or even hundreds of Gbps per physical layer link [1–3]. Over the past several years, a series of THz communication systems at record-high data rates have undergone significant development, accelerated by electronic and hybrid electronic-photonic techniques [4–9]. In particular, the seamless integration of THz wireless into commercial fiber-optic can complement the advantages of flexibility, high capacity, and wide-area coverage [6–9]. By using THz wireless fiber extenders in accordance with monolithic microwave integrated circuits, the first real-time 100 Gbps optical-wireless-optical transmission system at 300 GHz was demonstrated over two fiber-optic links and 0.5–500 m wireless link, and the 34 GBaud polarization division multiplexing quadrature-phase-shift-keying (PDM-QPSK) optical baseband signal was processed online via commercial digital coherent optics (DCO) modules [7]. However, the nonlinear harmonics distortion and the limited modulation bandwidth of solid-state devices can ultimately limit the data capacity for high bandwidth-consuming applications.

Optical-to-THz (O-T) conversion enabled by photonic heterodyne and THz-to-optical (T-O) conversion based on a hybrid optoelectronic approach have shown outstanding wideband tunable carrier frequency, high modulation index, and multi-carrier multiplexing in our previous studies [8, 9]. A 100/200 GbE real-time THz wireless transmission at 330–500 GHz was demonstrated in accordance with photonic techniques implementing commercial devices. Here, to our knowledge, we report the first real-time dual-λ (wavelength) optical-THz-optical transparent transmission system at 260 to 400 GHz using commercial DCO modules, which offers a record line rate of 2 × 240.558 Gbps over two spans of 20 km fiber and 3 m dual-polarization 2 × 2 multiple-input multiple-output (MIMO) wireless link without using THz power amplifier. The novel contributions of this work can be summarized as follows. (1) The bandwidth of the electronic THz receiver and the optical modulator is limited in comparison to 100/200 GbE real-time THz wireless transmission. We explore the record-high dual-λ 400 GbE transmission possibility and assess its performance with limited device bandwidth. (2) Two ultra-fast uni-travelling-carrier photodiodes (UTC-PDs) with WM-710 waveguide (260 to 400 GHz) are used, which are easy to connect with standard gain antennas or THz amplifier [10], conversely with restricted bandwidth. However, in our previous work, antenna-integrated photomixer module with WM-570 waveguide (330 to 500 GHz) was formed from a UTC-PD and a bow-tie or log-periodic antenna, which has ultra-wideband, nevertheless, is incompatible with standard devices. We experimentally demonstrate the possibility of dual-λ 400 GbE high-speed THz transmission using UTC-PD with WM-710 waveguide. (3) In this article, comprehensive supplementary video material has been provided. We present the deployed 400 GbE fiber-optics network to demonstrate video streaming service. The O-T and T-O converters are also displayed. The real-time fiber-THz-fiber transmission performance is first evaluated under various obstructions, such as paper, plastic, and metal.

Figure 1(a) depicts a schematic of the experimental setup. The deployed 400 GbE fiber-optics network can demonstrate video streaming service, which is enabled using two optical transport units, one streaming server and one client server. Commercial centum form-factor pluggable (CFP2)-DCO modules and dual-port quad small form-factor plug-

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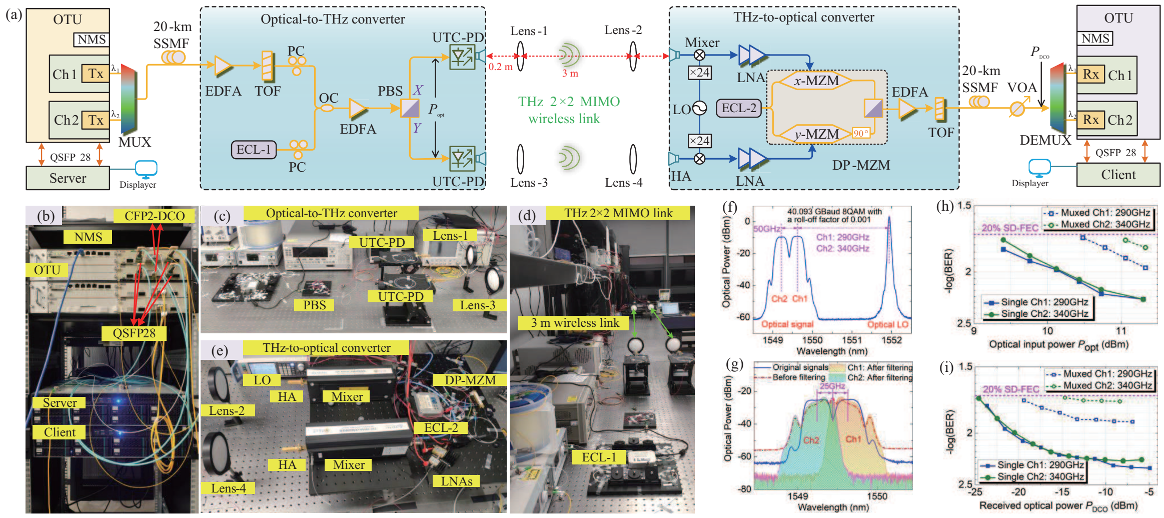

Figure 1 (Color online) Experimental setup and results of real-time dual-wavelength and dual-polarization optical-terahertz-optical seamless integration system. (a) Schematic diagram. Photograph of test-bed setup: (b) optical transceiver; (c) O-T converter; (d) THz 2 × 2 MIMO wireless link; (e) T-O converter. Measured optical spectrum (f) before UTC-PDs; (g) after DP-MZM with or without filtering. BER versus (h) optical input power into each UTC-PD; (i) received optical power of each DCO module.

gable 28 (QSFP28) modules are equipped on the line and client side, respectively. The network management system can set and monitor various parameters of the DCO modules, namely working mode, optical power, wavelength, and pre-BER. At the O-T converter, using two ultra-fast UTC-PDs operating at 260 to 400 GHz band, optical signals after polarization beam splitter with X- and Y-polarization components are photonic heterodyned with tunable external cavity laser (ECL-1) as an optical local oscillator (LO) to generate two parallel THz-wave wireless signals. Note that dual-polarization transmissions occur in the optical domain and not in the THz domain. Two polarization controllers before the optical coupler are used to adjust the incident polarization direction to maximize output THz power from UTC-PDs. Then, two parallel THz-wave signals are delivered over a 3-m 2 × 2 MIMO wireless link. Four identical lenses, 1-4, with 20 cm focal length and 10 cm diameter, were used to focus the wireless THz-wave to horn antennas (HAs). Each HA worked within 260–400 GHz and had 26 dBi gain. The O-T and T-O converters are placed at a height of 25 cm to avoid a multi-path effect from reflections on the table. At the T-O converter side, the hybrid optoelectronic down-conversion scheme is proposed to lift restrictions on the carrier frequency and the bandwidth of the optical components. The main idea behind this scheme is to down-mix the received parallel THz-wave signals to an intermediate frequency (IF) signal and then map to the optical domain using an off-the-shelf integrated dual-polarization Mach-Zehnder modulator (DP-MZM) working at optical-carrier-suppression point. Two cascaded electrical low-noise amplifiers with a gain of 27 dB and 16 dBm saturated output power are used to boost IF signals to drive DP-MZM (Fujitsu, FTM7980EDA). This commercial DP-MZM has a 3-dB bandwidth of 35 GHz and a low drive voltage of 3.5 V with an extinction ratio of 20 dB. A pass-band tunable optical filter (TOF) is set to filter out the corresponding sideband, which is seamlessly coupled into a span of 20 km standard single-mode fiber (SSMF) link for subsequent DCO real-time processing. Two wavelengths are muxed and demuxed by an optical multiplexer (MUX) and a demultiplexer (DEMUX), respectively. Photos of each module of the test bed are depicted in Figures 1(b)–(e).

We set each DCO module to work at 200 GbE transmission mode and modulate 40.093 GBaud dual-polarization-8 quadrature amplitude modulation (DP-8QAM) with a roll-off factor of 0.001 as an optical baseband signal. The dual-λ center frequency of Ch1 and Ch2 is set at 193.5 and 193.55 THz, which meets the standard commercial 50 GHz ITU-T grid. The frequency space between Ch1, Ch2 and optical LO is 290 and 340 GHz at 0.03 nm resolution, respectively, as shown in Figure 1(f). The measured optical spectra after DP-MZM with or without filtering by the TOF are shown in Figure 1(g). The frequency of down-converted IF signals after THz mixers are fixed at 25 GHz. One variable optical attenuator is used to evaluate BER performance. Note that, for the dual-λ case, Ch1 and Ch2 are separately tested by adjusting sinusoidal LO sources, but the data capacity of 2 × 200 GbE from THz transmitter remained unchanged. Furthermore, we also compare the single-λ case with the dual-λ case.

The BER versus optical input power into each UTC-PD is shown in Figure 1(h). Open FEC mode is utilized in each DCO module and consists of a Turbo product code encoder (4096/3552) with an iterative 20% soft-decision forward-error correction (SD-FEC) with a net coding gain of 11.6 dB according to OpenZR+ standard. The pre-FEC BER at 20% SD-FEC threshold is 2×10^{-2}. Each DCO module can support 20% SD-FEC threshold at pre-FEC BER of 2×10^{-2}. The impairments induced by wired and wireless links can be compensated using the real-time digital signal processing demodulator in the DCO modules, such as polarization mode dispersion and phase noise. Furthermore, the optical input optical into each UTC-PD remains below 12 dBm to avoid damaging UTC-PDs. We can observe that this system can successfully transmit at 290 and 340 GHz for both single-λ and dual-λ cases over two spans of 20 km SSMF in combination with 3 m wireless link. At the 20% SD-FEC threshold, there are approximately 1 and 1.5 dB optical input power penalties for the dual-λ case compared with the single-λ case at 290 and 340 GHz, respectively. These penalties are caused by the average power decrease of the dual-λ case. Moreover, Figure 1(i) shows the BER versus received optical power of each DCO module at 11.3 dBm $P_{\rm opt}$. The BER is gradually stable with the increasing power of $P_{\rm DCO}$. Furthermore, the input power penalty for the dual-case compared with the single-case is 5 and 10 dB at 290 and 340 GHz, respectively. These penalties are caused by the average power reduction of the dual-λ case, i.e., the UTC-PD frequency response at each carrier frequency for the dual-wavelength case is lower in comparison to the single case due to the limitation of input optical power. In this study, the THz emitting power and transmission distance are limited by the lack of THz power amplification. For practical 6G application scenarios in the future, the wireless distance of over 100 meters may be realized by using high-gain lens antennas, high-gain THz amplifiers or large-scale phased array antennas. Photonics combined with active electronic devices may extend THz wireless transmission distance. This photonics-enabled THz wireless and fiber seamless network demonstrated system can potentially support 6G applications, such as Tbps integrated access and backhaul.

In conclusion, we have experimentally demonstrated the first dual-λ real-time optical-THz-optical transmission system at 290 and 340 GHz, which offers a record line rate of up to 2 × 240.558 Gbps over hybrid fiber and THz wireless links. The photonics-enabled O-T and T-O converters are compatible with commercial existing fiber-optic infrastructures in a cost-effective manner. In the years ahead, the ongoing research and development on integrated optoelectronic THz-optics systems with kilometer-level distance transmission would push forward the widespread application of the 6G THz wireless communication.

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Supporting information Video. 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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