Integrated Dual-DFB Laser for 408 GHz Carrier Generation Enabling 131 Gbit/s Wireless Transmission over 10.7 Meters

Shi Jia[1], Mu-Chieh Lo[2], Lu Zhang[3,6], Oskars Ozolins[4,3], Aleksejs Udalcovs[4], Deming Kong[1], Xiaodan Pang[3], Xianbin Yu[5], Shilin Xiao[6], Sergei Popov[3], Jiajia Chen[3], Guillermo Carpintero[2], Toshio Morioka[1], Hao Hu[1], Leif K. Oxenløwe[1]

[1]*DTU Fotonik, Technical University of Denmark, DK-2800, Kgs. Lyngby, Denmark*
[2]*Universidad Carlos III de Madrid, 28911 Leganés, Madrid, Spain*
[3]*KTH Royal Institute of Technology, 164 40 Kista, Sweden*
[4]*NETLAB, Research Institutes of Sweden AB, 164 25 Kista, Sweden*
[5]*College of Information Science and EE, Zhejiang University, Hangzhou 310027, China*
[6]*School of SE-IEE, Shanghai Jiao Tong University, Shanghai 200240, China*
Author e-mail address: shijai@fotonik.dtu.dk; huhao@fotonik.dtu.dk; guiller@ing.uc3m.es; xiaodan@kth.se

Abstract: A monolithically integrated dual-DFB laser generates a 408 GHz carrier used for demonstrating a record-high single-channel bit rate of 131 Gbit/s transmitted over 10.7 m. 16-QAM-OFDM modulation and specific nonlinear equalization techniques are employed.

OCIS codes: (060.4510) Fiber optics and optical communications; (060.5625) Radio frequency photonics.

1. Introduction

The forecasted demands for broadband wireless applications in 5G and beyond have driven the research of wireless communication to the Terahertz band (ranging from 0.3 to 10 THz) [1] to exploit the large available bandwidth. In [2], Nagatsuma et al identify realistic target distances for different frequency bands with the 10-100 m range recommended for indoor communications for frequencies ranging from 350-910 GHz. To fully exploit the new frequency bands, extensive research has been conducted to obtain high data rates transmittable at these frequencies alongside the efforts to reach longer distances. Fig. 1 shows a plot of demonstrated bit rate and reach for the 350-910 GHz band [2-9]. For photonic schemes, high bit rates may be obtained by optical multiplexing techniques often yielding data rates of 100 Gbit/s and above [4-7]. However, such multiplexing techniques increase the system cost and complexity. Single-channel wireless transmission with a data rate beyond 100 Gbit/s has recently been demonstrated [9] albeit over a very short distance. Table 1 shows reported longest reach wireless THz transmission demonstrations revealing bitrate and transmitter THz power in different frequency bands, and for comparison, the normalized transmitter THz power per bitrate and distance [8, 10, 11].

Table 1: The comparison of the normalized transmitter THz power of the reported longest-level demonstrations.

Demonstrations	10 dBm, 35 m, 1 Gbit/s@400 GHz [8]	-15 dBm,100 m, 50 Gbit/s@300 GHz [10]	0 dBm, 110 m, 93 Gbit/s@300 GHz [11]	-24 dBm, 10.7 m, 131 Gbit/s@400 GHz [**This work**]
Normalized power (J/bit/m)	2.9×10^{-13}	6×10^{-18}	9×10^{-17}	$\mathbf{2.9\times10^{-18}}$

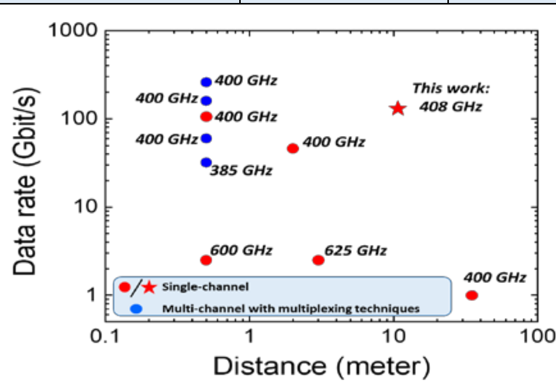

Fig. 1. State-of-the-art wireless bit rate vs. distance for frequencies above 350 GHz.

In this paper, we demonstrate the first single-channel THz photonic-wireless transmission obtaining both high bit rate and long reach above the 100 Gbit/s and 10 m targets. We generate a 408 GHz carrier using a monolithically integrated dual-distributed feedback (DFB) laser chip attached to a photo-mixing uni-travelling carrier photodiode (UTC-PD) with a THz antenna, and successfully transmit a net rate of 131 Gbit/s over 10.7 m. To the best of our knowledge, this is the highest data rate for a single-channel THz wireless transmission and the largest capacity-distance product for frequencies ≥350 GHz. Furthermore, its normalized transmitter THz power per bitrate and distance is the lowest.

2. Experimental setup

At the transmitter, two continuous waves (CWs) at 1555.675-nm and 1558.975-nm are generated by a dual-DFB laser chip [12], as shown in the inset of Fig. 2(a). The two freely tunable DFB lasers are monolithically integrated with a 3-dB multimode interference (MMI) coupler in a heterodyne configuration. Each DFB laser is controlled with an injection current and a heater current. This photonic integrated circuit (PIC) was developed in a generic foundry approach. The wavelength spacing between the two CWs is controllable within the range of 0-10.7 nm, resulting in a

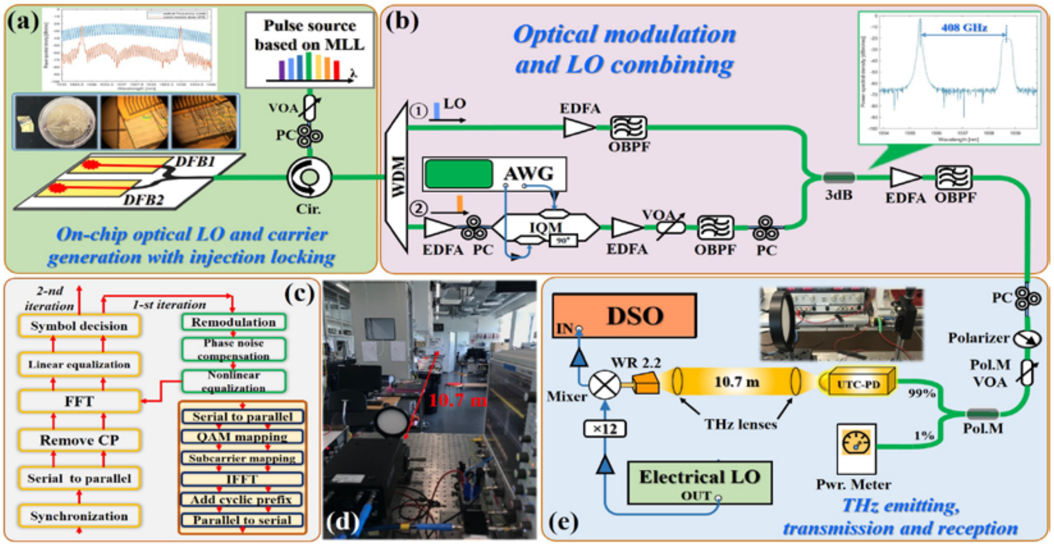

Fig. 2. Experimental configuration of 131.21 Gbit/s single-channel photonic-wireless 16-QAM-OFDM transmission system over 10.7 m: (a) On-chip optical LO and carrier generation with injection locking. (b) Optical modulation and LO combining. (c) The structure of the DSP routine. (d) The picture of the actual THz link. (e) THz emitting, transmission and reception.

continuously tunable beat note from microwave to THz frequencies (up to ~1.4 THz). For a phase-stabilized beat note, an off-the-shelf mode-locked laser (MLL) which emits a 9.951-GHz-spacing optical frequency comb is used to injection-lock the two CW modes, making them frequency and phase correlated. In the experiment, the spacing between the two DFB lasers is tuned to be 408 GHz in order to generate the carrier frequency.

The experimental setup is shown in Fig. 2. The two coherent tones generated in the dual-DFB laser chip with 408 GHz spacing are separated by a demultiplexer. One tone is used as an optical local oscillator (LO) for heterodyne mixing in order to generate the THz wave. The other tone is used for carrying data and launched into an in-phase (I) and quadrature (Q) optical modulator (IQM).

A two-channel 64-GSa/s arbitrary waveform generator (AWG) is used to generate the IQ-OFDM signal. The length of the inverse fast Fourier transform (IFFT) and cyclic prefix (CP) of the IQ-OFDM signal are set to 1024 and 16, respectively, and the first subcarrier is set to null. The binary sequence used to generate the OFDM symbols is a random sequence generated from MATLAB software. The modulated 16-QAM-OFDM (quadrature amplitude modulation-orthogonal frequency-division multiplexing) optical signals after the IQM are amplified by an erbium-doped fiber amplifier (EDFA) followed by an optical band-pass filter (OBPF). Here, a variable optical attenuator (VOA) is used to control the power of the optical signal before combining the optical LO, to keep the power ratio balanced between the optical LO and signal for the highest photo-mixing efficiency in the uni-travelling carrier photodiode (UTC-PD) [13].

The baseband signal and the optical LO are polarization aligned, and then combined before launching into the broadband UTC-PD. A polarization maintaining (Pol. M) VOA is used to control the optical power launched into the UTC-PD. The optical spectrum of the combined signal and LO is shown in the inset of Fig. 2 (b). At the output of the UTC-PD, a THz signal with carrier frequency centered at 408 GHz are generated and emitted into a 10.7-m line-of-sight (LOS) wireless link, as shown in Fig. 2(d). A pair of THz lenses with a 100-mm diameter and 200-mm focus length is used to collimate the THz beam.

At the receiver, the THz signal is down-converted to an intermediate frequency (IF) by employing a sub-harmonic Schottky mixer operating in the 0.3-0.5 THz band, driven by a 12-time (×12) frequency multiplied electrical LO. The electrical LO is tuned to be 32 GHz, resulting in a corresponding IF carrier frequency of 24 GHz. The IF signal is amplified by an RF amplifier with 45 GHz bandwidth and then converted to digital samples in a 160 GSa/s real-time digital sampling oscilloscope (DSO) with 63 GHz analog bandwidth. The digital signals are processed and analyzed offline with a digital signal processing (DSP) routine.

The structure of the DSP routine is shown in Fig. 2(c). The channel equalization is composed of linear equalization (LE), phase noise compensation (PNC) and nonlinear equalization (NLE). First, the signal after the FFT module passes through the pilot based one-tap LE, which is used to compensate the system linear response and to reduce the system additive noise influence. After LE, the signal is equalized with a least-squares method-based PNC to reduce the impairment from phase noise. After the PNC, a simplified Volterra series nonlinear model is used for estimating the nonlinearity impairment, which considers the 2nd-order and the 3rd-order distortion terms.

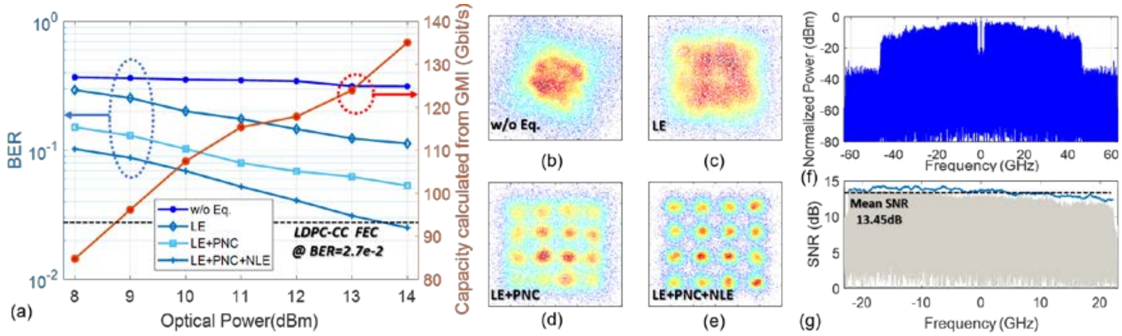

Fig. 3. (a) BER versus the optical power launched into the UTC-PD for 4 cases with different combinations of DSP modules. (b-e) Constellations for 4 cases with 14 dBm optical power and different combinations of DSP modules. (f) The electrical spectrum of the 16-QAM-OFDM signal before down conversion. (g) The SNR versus the frequqency after down conversion.

3. Experimental results

The single-channel THz signal is evaluated after the 10.7-m wireless transmission. As shown in Fig. 3(a), the BER performance for four cases of different DSP modules combined (w/o equalization, LE, LE+PNC, LE+PNC+NLE) have been measured as a function of the optical power launched into the UTC-PD. For the case of nonlinear DSP (LE+PNC+NLE) employed, a BER below low-density parity-check convolutional codes (LDPC-CC) forward error correction (FEC) threshold (2.7 e-2, 20%-OH, the pre-FEC BER was calculated from the given Q factor in dB as $(1/2)erfc(10^{5.7dB/20}/\sqrt{2})$) [14, 15] is successfully achieved. The 16-QAM-OFDM has a total bandwidth of 44.43 GHz, which corresponds to a gross bit rate of 157.46 Gbit/s (subtracting the pilot overhead) and a net rate of 131.21 Gbit/s after subtracting the FEC overhead. The capacity calculated by the generalized mutual information (GMI) [16] is also presented, and the capacity of 14 dBm optical power is 134.56 Gbit/s, which has ~2.5% variation with post-FEC capacity. The corresponding signal constellations captured at an optical power of 14 dBm with different DSP modules are shown in Fig. 3(b)-(e) respectively. The electrical spectra of the 44.43 GHz OFDM signal both before and after down conversion and filtering are shown in Fig. 3(f)-(g) respectively, with the IF set to 24 GHz. The performance of the system here is limited by the SNR of the received signal, as shown in Fig. 3(g), which is mainly due to the limited conversion efficiency of the UTC-PD (0.15 A/W) and the sub-harmonic Schottky mixer.

4. Conclusions

We have experimentally demonstrated a single-channel 131.21 Gbit/s net rate THz-band wireless transmission over 10.7-m wireless distance, employing 16-QAM-OFDM modulation and nonlinear DSP flow. The scheme of using a monolithic dual-DFB laser chip THz generation shows a great potential for fully integrated THz transmitters.

Acknowledgements

We would like to thank the support by the EU H2020 Marie Sklodowska-Curie grant agreement no. 713683 (COFUNDfellowsDTU), the EU H2020 Marie Skłodowska-Curie Grant agreement no. 642355 FiWiN5G, the Danish center of excellence CoE SPOC under Grant DNRF123, the Villum young investigator program grant of 2MAC and the China Postdoctoral Science Foundation under Grant 2017M611990, the Swedish Research Council (VR), the Swedish Foundation for Strategic Research (SSF), Göran Gustafsson Foundation, the Swedish ICT TNG, the EU H2020 MCSA-IF Project NEWMAN (#752826), VINNOVA funded SENDATE-EXTEND and SENDATE-FICUS, National Natural Science Foundation of China (#61331010, 61722108, 61775137, 61671212, 61771424).

References

[1] J. Federici and L. Moeller, "Review of terahertz and subterahertz wireless communications," J. Appl. Phys. Vol. 107, p. 111101 (2010).

[2] T. Nagatsuma, et al., "Advances in Terahertz Communications Accelerated by Photonics," Nature Photon., Vol. 10, p. 371 (2016).

[3] T. Nagatsuma, et al., “THz Communication Systems,” Proc. OFC, Tu3B.1, San Diego (2017).

[4] S. Jia, et al., “THz Photonic Wireless Links with 16-QAM Modulation in the 375-450 GHz Band,” Opt. Express, Vol. 24, p. 23777 (2016).

[5] X. Yu, et al., “160 Gbit/s Photonics Wireless Transmission in the 300-500 GHz Band,” APL Photon., Vol. 1, p. 08131.211 (2016).

[6] X. Pang, et al., “260 Gbit/s Photonic-Wireless Link in the THz Band,” Proc. IEEE Photon. Conf., Paper PD1-2, Hawaii (2016).

[7] X. Li et al., “Photonics-aided 2×2 MIMO wireless terahertz-wave signal transmission system with optical polarization multiplexing,” Opt. Express, Vol. 25, p. 33236 (2017).

[8] J. Ma, et al., "Channel Performance for Indoor and Outdoor Terahertz Wireless Links," APL Photon., Vol. 3, p. 051601 (2018).

[9] S. Jia, et al., “0.4 THz Photonic-Wireless Link With 106 Gb/s Single Channel Bitrate,” J. Lightw. Technol., Vol. 36, p. 610 (2018).

[10] T. Nagatsuma, et al., "300-GHz-band Wireless Transmission at 50 Gbit/s over 100 Meters," Proc. IRMMW-THz, 1-2, Copenhagen (2016).

[11] T. Harter, et al., "110-m THz Wireless Transmission at 100 Gbit/s Using a Kramers-Kronig Schottky Barrier Diode Receiver," Proc. ECOC, PDP 1-3, (2018).

[12] M. Lo, et al., "Monolithically Integrated Microwave Frequency Synthesizer on InP Generic Foundry Platform," J. Lightw. Technol., vol. 36, p. 4626 (2018).

[13] T. Ishibashi, et al., “Unitraveling-Carrier Photodiodes for Terahertz Applications,” IEEE J. Sel. Topics Quantum Electron., Vol. 20, no. 6, p. 3804210 (2014).

[14] D. Chang et al., “LDPC Convolutional Codes using Layered Decoding Algorithm for High Speed Coherent Optical Transmission,” Proc. OFC, OW1H.4, Los Angeles (2012).

[15] E. Agrell et al., “Information-Theoretic Tools for Optical Communications Engineers,” Proc. IPC, (2018).

[16] A. Alvarado, et al., “Replacing the soft-decision FEC limit paradigm in the design of optical communication systems,” J. Lightw. Technol., vol. 33, no. 20, pp. 4338–4352, (2015).