High symbol rate 200-GBd PDM-QPSK Transmission over 3520 km Using Ultra-broadband InP-DHBT Analogue Multiplexer

Masanori Nakamura(1), Takeo Sasai(1), Fukutaro Hamaoka(1), Munehiko Nagatani(1, 2), Hiroshi Yamazaki(1, 2), Teruo Jyo(2), Miwa Mutoh(2), Yuta Shiratori(2), Hitoshi Wakita(2), Takayuki Kobayashi(1), Hiroyuki Takahashi(1, 2), Kisaka Yoshiaki(1), Yutaka Miyamoto(1)

(1) NTT Network Innovation Laboratories, NTT Corporation, msnr.nakamura@ntt.com
(2) NTT Device Technology Laboratories, NTT Corporation

Abstract *Long-haul transmission over 3520 km in a 4.725-THz WDM configuration with 225-GHz-spacing in the C-band has been successfully demonstrated with a high-symbol-rate 200-GBd polarization-division-multiplexed QPSK signal, which was generated using in-house >110-GHz analogue multiplexers and >130-GHz-bandwidth electrical amplifiers based on ultra-broadband indium phosphide technologies. ©2023 The Author(s)*

Introduction

High-capacity and long-haul optical transmission systems based on digital coherent technologies have been becoming essential as communications traffic continues to grow dramatically. Using electrically generated high symbol rate signals is a promising way to increase capacity per wavelength and transmission distance without increasing optical devices. Bandwidth (BW) extension techniques [1, 2] have been intensively studied to increase the symbol rate with high-speed electrical signalling. They have been used to generate 200-GBd-class signals, including a 192-GBd quadrature phase shift keying (QPSK) signal using an analogue multiplexer integrated indium phosphide (InP) based in-phase and quadrature modulator (IQM) module [3] and a 200-GBd probabilistically constellation-shaped (PCS) 64 quadrature amplitude modulation (QAM) signal based on digital interleaving and a thin-film IQM [4]. High symbol rate and large capacity per wavelength transmission experiments have recently been conducted using a high-speed silicon–germanium (SiGe) digital-to-analogue converter (DAC) based arbitrary waveform generator (AWG) with an ~80-GHz BW. For example, transmission with a net bitrate of >2-Tb/s/wavelength over 240 km with a 176-GBd PCS-144QAM signal was achieved using a >130-GHz BW InP double-heterojunction bipolar transistor (DHBT) electrical amplifier module [5], and 260-GBd polarization division multiplexing (PDM) QPSK signal transmission over 100 km was achieved using a 110-GHz-BW thin-film lithium niobate (LN) IQM [6].

Along with these high-speed transmission technologies, ones for long-haul transmission are also essential. For long-haul transmission, a high symbol rate signal is effective because high noise tolerance can be achieved compared with higher

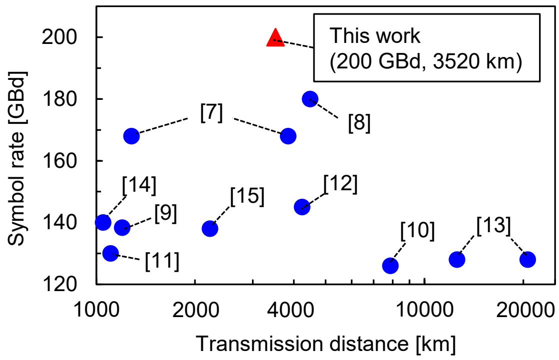

Fig. 1: Symbol rate vs. transmission distance for high symbol rate (>120 GBd) and long-haul transmission (>1000 km) experiments

order QAM. Long-haul transmission over 1000 km with a symbol rate of >120-GBd has also been demonstrated, as illustrated in Fig. 1 [7–15]. A 168-GBd PCS-16QAM signal was transmitted over 3840-km through 80-km spans of pure-silica core fibre (PSCF) with a hybrid erbium-doped fibre amplifier (EDFA) and backward Raman amplification in wavelength division multiplexing (WDM) configuration [7]. Also reported was 180-GBd electrical time-division multiplexing (ETDM) PDM-QPSK single-channel transmission over 4480 km through standard single-mode fibre [8]. Even higher symbol rate long-haul signal transmission is required for next-generation optical transmission systems.

In this paper, we have demonstrated 200-GBd PDM-QPSK transmission using in-house ultra-broadband InP-DHBT-based >110-GHz-BW analogue multiplexers and >130-GHz-BW electrical amplifiers. The net bitrate of the 200-GBd signal was 650 Gb/s after 3520-km transmission, where the transmission over a transmission line consisting of 80-km spans of PSCF and EDFAs. The potential spectrum efficiency was 2.88-b/s/Hz in a 225-GHz-spaced 4.725-THz full C-band WDM configuration.

High symbol rate transmitter using ultra-broadband InP-DHBT Analogue Multiplexers

We generate the 200-GBd signal by using analogue multiplexers (AMUXs). Figure 2(a) illustrates the in-house InP-DHBT analogue multiplexing module (13.6 × 13.6 × 5 mm) [16]. Two low-speed signals from sub-DACs and a clock signal are input, and a multiplexed high-speed signal is output. The module has a >110-GHz BW as shown in Fig. 2(b). The desired high-speed signal is generated with this AMUX module as follows.

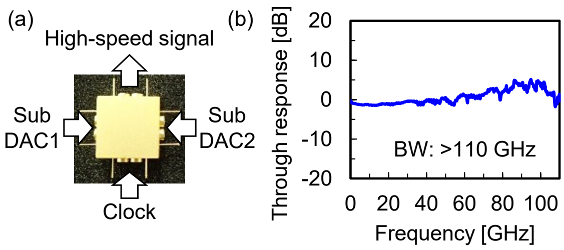

Fig. 2: (a) AMUX module; (b) its electrical response

The configuration of AMUX modules is shown in Fig. 3(a). In offline Tx-DSP, 200-GBd QPSK signals were generated from a bit sequence derived from the Mersenne Twister pseudorandom number generator. The frame length was about one million symbols (pilot symbols comprised 1.59%). The high-speed signals were decomposed into two low-speed signals by pre-processing using a digital-pre-processed analogue-multiplexed (DP-AM-) DAC using a half-clock frequency scheme [17]. Digital pre-equalization was carried out using a fixed linear equalizer to compensate for the frequency response and the in-band crosstalk in the DP-AM-DAC scheme. A four-channel 100-GSa/s AWG with a BW of 65-GHz was used as the sub-DACs for DP-AM-DAC. The 200-GBd signal was generated by the AMUX modules and the AWG, where the AMUX modules and AWG were operated with 50-GHz clocks. The signals were amplified by >130-GHz-BW electrical amplifier modules [18]. To achieve sufficient gain to drive the LN-IQM, the amplifier modules were concatenated, as shown in Fig 3(a). The LN-IQM had a 35-GHz BW and modulated a continuous wave from a laser diode (LD) with a linewidth of ~10 kHz. A PDM signal was emulated by using a PDM emulator with a 35-m delay line (175-ns delay). Optical equalization (OEQ) was performed for the PDM signal to flatten the optical spectrum.

The receiver (Fig. 3(b)) detected the signal using a coherent receiver composed of a dual-polarization optical hybrid and four 100-GHz bandwidth-balanced photodiodes after optical band-pass filtering (OBPF). The linewidth of the local oscillator (LO) input to the optical hybrid was ~10 kHz. The signals were digitalized with a 256-GSa/s digital storage oscilloscope with a 113-GHz bandwidth. In offline Rx-DSP, chromatic dispersion was compensated for by using static frequency domain (FD) equalization. The signal was recovered using FD-8×2 multi-input multi-output (MIMO) adaptive equalization with a block length of 4096 for fast Fourier transformation, and a digital phase-locked loop (PLL) [19]. Normalized generalized mutual information (NGMI) was then derived from bit-wise log likelihood ratios.

The single-channel optical spectra with and without OEQ are shown in Fig. 4(a). The 200-GHz BW signal generation was confirmed. The BW limitations of the LN-IQM were compensated for by using M-shaped OEQ, as shown in Fig. 4(a). Figure 4(b) shows constellation diagrams in a single-channel back-to-back configuration. The demodulated signal had a signal-to-noise ratio (SNR) of 8.88 dB. The SNR was limited by the severe BW limitations of LN-IQM.

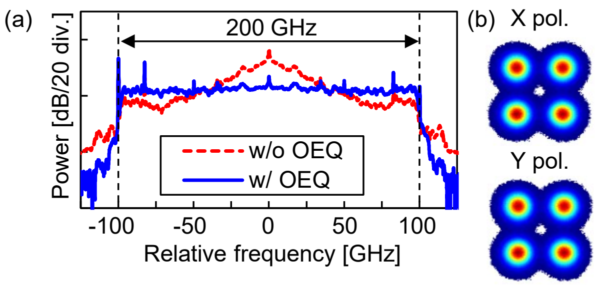

Fig. 4: Single-channel back-to back configuration for (a) optical spectra with and without OEQ and (b) constellation diagrams.

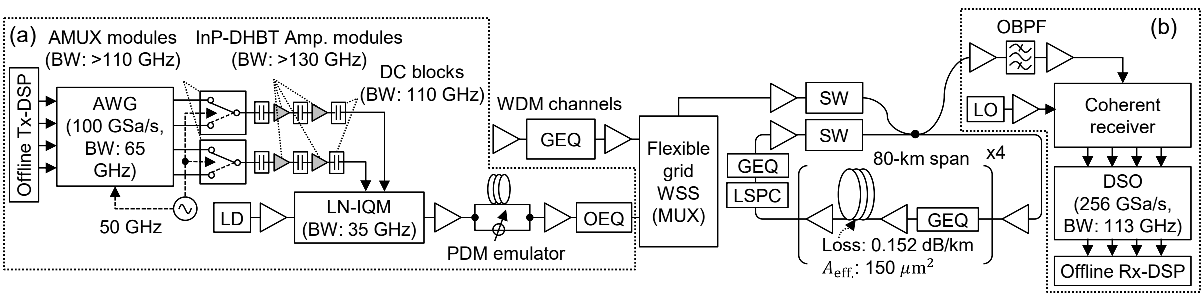

Fig. 3: Experimental setup for high symbol rate long-haul transmission: (a) transmitter; (b) receiver

Transmission experiments

We evaluated long-haul transmission of high symbol rate signal generated by the AMUX modules. A 200-GBd PDM-QPSK signal with interference WDM signals was input into a recirculating loop for transmission. An interference channel with a 225-GHz grid-spaced 4.725-THz WDM signal was emulated using amplified spontaneous emission from the EDFA where the optical spectrum was flattened using an optical gain equalizer (GEQ). The main signal of 200-GBd PDM-QPSK was multiplexed with the WDM signal in a flexible grid wavelength selective switch (WSS). The generated WDM signal was fed into a re-circulating loop consisting of four spans of 80-km PSCF, with GEQs to flatten the gain slope, and a loop synchronous polarization controller (LSPC) at the end of the loop. An EDFAs was used for each 80-km span of PSCF to compensate for fibre loss.

Figure 5 shows the optical spectra before and after transmission. The channel under test was 193.775 THz at the centre frequency of the WDM signal. The launch power for each fibre span was set to 9 dBm/channel. Figure 6 shows NGMI as a function of transmission distance for the 200-GBd PDM-QPSK signals. The measured NGMI of the signals after 3520-km transmission was observed to be better than the NGMI threshold of 0.857 for 20.94% overhead forward error correction (FEC) code [20]. If the FEC code with a code rate of 0.826 is assumed, the net bitrate of the 200-GBaud PDM-QPSK signals was 650 Gb/s [2 pol. × 2 bit × 200 GBaud × 0.826 / 1.0159].

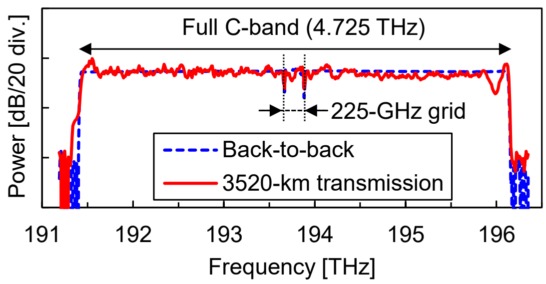

Fig. 5: Optical spectra of WDM signal before and after 3520-km transmission.

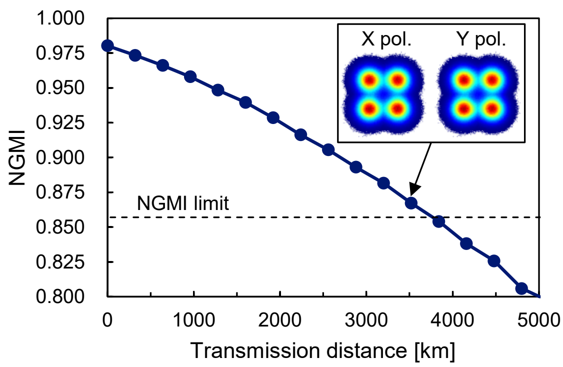

Fig. 6: NGMI vs. transmission distance.

The potential spectrum efficiencies of the 200-GBaud PDM-QPSK signal in the 225-GHz-grid WDM configuration was 2.88-b/s/Hz. These results demonstrate that long-haul transmission of 200-GBd-signals can be achieved with a high symbol rate and ultra-broadband InP-DHBT analogue multiplexing.

Conclusions

We have successfully demonstrated 200-GBd PDM-QPSK signal transmission using in-house ultra-broadband InP-DHBT-based >110-GHz-BW analogue multiplexers and >130-GHz-BW electrical amplifiers. The net bitrate of the 200-GBd signal was 650 Gb/s after 3520-km transmission with 80-km spans of PSCF and EDFAs. The potential spectrum efficiency is 2.88-b/s/Hz in a 225-GHz-spaced 4.725-THz full C-band WDM configuration. These results demonstrate the feasibility of long-haul signal transmission based on ultra-broadband InP-DHBT analogue multiplexing.

References

[1] H. Yamazaki, et al., “160-Gbps Nyquist PAM4 transmitter using a digital-preprocessed analog-multiplexed DAC”, in Proc. ECOC2015, PDP.2.2 (2015). DOI: 10.1109/ECOC.2015.7341681

[2] X. Chen, et al, “All-Electronic 100-GHz Bandwidth Digital-to-Analog Converter Generating PAM Signals up to 190 GBaud”, *J. Lightw. Technol.* 35, 411-417 (2017). DOI: 10.1109/JLT.2016.2614126

[3] M. Nakamura, et al., “192-Gbaud Signal Generation Using Ultra-Broadband Optical Frontend Module Integrated with Bandwidth Multiplexing Function”, in Proc. OFC2019, M4I.4 (2019). DOI: 10.1364/OFC.2019.Th4B.4

[4] X. Chen, et al., "Transmission of 200-GBaud PDM Probabilistically Shaped 64-QAM Signals Modulated via a 100-GHz Thin-film LiNbO3 I/Q Modulator", in Proc. OFC2021PDP, F3C.5. DOI: 10.1364/OFC.2021.F3C.5

[5] M. Nakamura, et al., “Over 2-Tb/s Net Bitrate Single-carrier Transmission Based on >130-GHz-Bandwidth InP-DHBT Baseband Amplifier Module”, in Proc. ECOC2022PDP, Th3C.1. (2022).

[6] H. Mardoyn, et al., “First 260-GBd Single-Carrier Coherent Transmission over 100 km Distance Based on Novel Arbitrary Waveform Generator and Thin-Film Lithium Niobate I/Q Modulator”, in Proc. ECOC2022PDP, Th3C.2. (2022).

[7] M. Nakamura et al., "1.0-Tb/s/λ 3840-km and 1.2-Tb/s/λ 1280-km Transmissions with 168-GBaud PCS-QAM Signals Based on AMUX Integrated Frontend Module", in Proc. OFC2022, W3C.1. (2022). DOI: 0.1364/OFC.2022.W3C.1

[8] G. Raybon et al., "180-GBaud All-ETDM Single-Carrier Polarization Multiplexed QPSK Transmission over 4480 km", in Proc OFC2018PDP, Th4C.3 (2018). DOI: 10.1364/OFC.2018.Th4C.3

[9] J. Zhang, et. al., "Generation and Transmission of High Symbol Rate Single Carrier Electronically Time-Division

Multiplexing Signals", Photonics Journal, vol. 8, no. 2, (2016). DOI: 10.1109/JPHOT.2016.2530565

[10] A. Matsushita et al., "Super-Nyquist 9-WDM 126-GBaud PDM-QPSK Transmission over 7878 km using Digital-Preprocessed Analog-Multiplexed DAC for Long-Haul Applications", in Proc. ECOC2016, W.3.D.2 (2016).

[11] F. Pittalà, et al., "Single-carrier coherent 930G, 1.28T and 1.60T field trial", in Proc. ECOC 2021, paper Th2C1.1 (2021). DOI: 10.1109/ECOC52684.2021.9605966

[12] S. Almonacil et al., "Long-haul Transmission of 1 Tb/s Data Rate Channel with Inline Filtering based on 145 GBd Dual Polarization 16QAM", in Proc OFC2023 W4H.2 (2023).

[13] J Esparza et al., "128GBd record QPSK transmission over 20 631 km and PCS16QAM transmission over 12 558 km using InP technology Platform", in Proc OFC2023, Tu2G.2. (2023).

[14] A. Zhang, et al., "32× 800Gb/s/carrier DWDM coherent transmission over 1050km EDFA amplified G.652 fiber using OE-MCM prototype with up to 140GBd symbol rate", ACP2022, paper 650. (2022). DOI: 10.1109/ACP55869.2022.10089135

[15] Thomas Richter et. al., "1 Tb/s and 800 Gb/s real-time transmission at 138 GBd over a deployed ROADM network with live traffic", in Proc, OFC2023PDP, Th4C.1. (2023).

[16] M. Nagatani, et al., "A Beyond-1-Tb/s Coherent Optical Transmitter Front-End Based on 110-GHz-Bandwidth 2:1 Analog Multiplexer in 250-nm InP DHBT", *IEEE J Solid-State Circuits*, vol. 55(9), pp. 2301-2315 (2020). DOI: 10.1109/JSSC.2020.2989579

[17] H. Yamazaki, et al., "Discrete Multitone Transmission at Net Data Rate of 250 Gb/s Using Digital-Preprocessed Analog-Multiplexed DAC With Halved Clock Frequency and Suppressed Image", *J. Lightwave Technol.*,35(7), 1300–1306 (2017). DOI: 10.1109/JLT.2017.2650205

[18] T. Jyo, et al., "An Over 130-GHz-Bandwidth InP-DHBT Baseband Amplifier Module", in *Proceedings IEEE BiCMOS and Compound Semiconductor Integrated Circuits and Technology Symposium (BCICTS) 2021*, 1b.1. (2021). DOI: 10.1109/BCICTS50416.2021.9682479

[19] M. Nakamura, et al., "High Information Rate of 128-GBaud 1.8-Tb/s and 64-GBaud 1.03-Tb/s Signal Generation and Detection Using Frequency-Domain 8×2 MIMO Equalization", in Proc. OFC2022, M3H.1, (2022). DOI: 10.1364/OFC.2022.M3H.1

[20] M. Nakamura, et al., "Spectrally Efficient 800 Gbps/Carrier WDM Transmission with 100-GHz Spacing Using Probabilistically Shaped PDM-256QAM", in Proc. ECOC2018, We3G.5 (2018). DOI: 10.1109/ECOC.2018.8535182