180-GBaud All-ETDM Single-Carrier Polarization Multiplexed QPSK Transmission over 4480 km

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Abstract: We demonstrate PDM-QPSK transmission over 4480 km at a record all-electronically multiplexed symbol rate of 180 GBaud, providing a line rate of 720 Gb/s on a single optical carrier enabled by high-speed InP-DHBT selectors.

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1. Introduction

The single channel bit rate of coherent optical transmission systems is continuously increasing with advances in digital signal processing (DSP), modulation formats, and high-speed electrical and electro-optical components. A key factor in achieving higher bit rates are increases in symbol rates, which require innovations in high-speed electronics and optoelectronic components, with an increase only of around 10% per year. Currently, symbol rates in commercial coherent optical systems range from 28 GBaud to 56 GBaud, enabling single-carrier systems to carry bit rates of 400 Gb/s using polarization-division multiplexed (PDM) quadrature amplitude modulation (QAM) [1]. There are clear indications that commercial systems will soon be pushing to 65-70 GBaud [2]. In research, the highest-symbol-rate electronically time division multiplexed (ETDM) systems without an integrated digital-to-analog converter (DAC) use 138.4-Gbaud PDM-QPSK (553.6 Gb/s line rate) [3]. Using high-speed DACs, 90-GBaud and 100-GBaud PDM-64-QAM for a line rate of 1.08 Tb/s [4] and 1.2 Tb/s [5] has been achieved. Using optical laboratory techniques such as spectral synthesis through electrical or optical digital band interleaving (DBI), optical symbol rates as high as 180 GBaud (BPSK/optically emulated QPSK [6]) and 127.9 GBaud [7], as well as optical time division multiplexing (OTDM) up to 1.28 TBaud [8] has been reported. However, the preferred approach for commercial viability remains ETDM, and in this paper, we extend previous 138.4-GBaud record by 30%, to 180 GBaud. We report the generation of a 180-GBaud (720-Gb/s line rate) PDM-QPSK single-carrier signal using all-ETDM with new Indium Phosphide (InP) Double Heterojunction Bipolar Transistor (DHBT) selectors to generate 180-Gb/s electrical signals. The signals are applied to a conventional $LiNbO_3$ in-phase/quadrature (I/Q) modulator without any transmitter digital signal processing applied. Single-channel transmission over 4480 km of standard single mode fiber (SSMF) using erbium-doped fiber amplifiers is achieved. The signals are detected using ~100-GHz bandwidth balanced photodiodes connected to a >110-GHz (256-GS/s) Keysight oscilloscope.

2. 180-Gbaud PDM-QPSK Transmitter

The transmitter is shown in Figure 1. Pseudorandom bit sequences (PRBS) of length 2^{15}-1 are generated at 45 Gb/s and multiplexed to 90 Gb/s using two 2:1 electronic multiplexers. These signals are then delay-decorrelated again and multiplexed to 180 Gb/s using newly fabricated and packaged 2:1 InP DHBT selectors that are shown in the photograph in Figure 2a. The electrical eye diagram shown in Fig 1b is measured with a Keysight 110-GHz bandwidth remote head at the 180-Gb/s selector output. This is a differential measurement and the differential amplitude is ~500mV peak to peak. The 2:1-Selector chip is fabricated in III-V Lab's 0.7-µm InP-DHBT technology [9]. With latest technological improvements, the transistor exhibits 400-GHz f_T and f_{max} at 8-mA/µm² current density and > 4.5-V breakdown voltage, allowing comfortable current and voltage amplitude swings. To achieve very-high-speed operation, the 2:1-Selector design reported in [10] has been improved both at electrical and layout levels [11]. Input data buffers were optimized for 100-Gb/s operation, while a new input clock buffer has been designed to deal with low clock levels available at frequencies around 100 GHz. The module consumes 0.5 to 0.8 W, at 250- to 730-mV_{pp} differential output swing. The packaged device shown in Fig. 2a is composed of a 2:1-Selector chip in a compact brass housing with minimum-length Al_20_3-ceramic-based coplanar-waveguide (CPW) transmission lines and 5 GPPO connectors (3 at the input side, 2 at the output side). The broadband operation of the module is made possible by a custom GPPO-to-CPW brazing process that is compatible with very small dimensions (a few tens of µm). As a result, the RF integrity is ensured up to very high frequencies, allowing a record operation speed of 180 Gb/s of the fully packaged module.

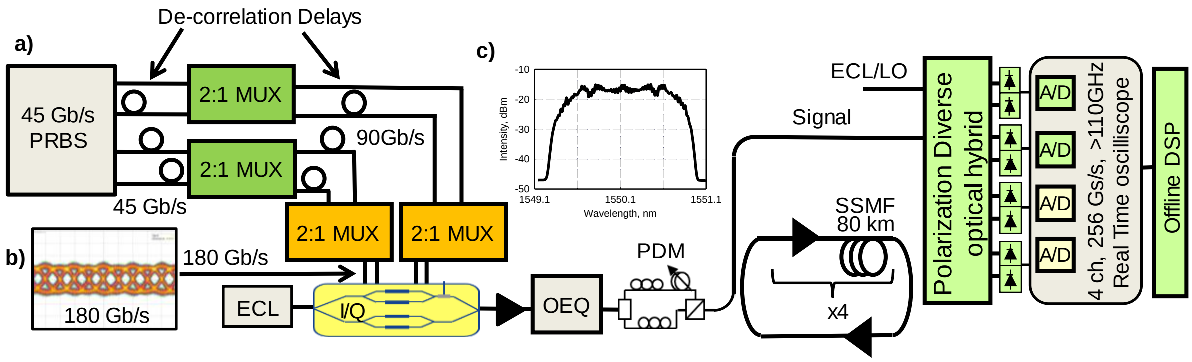

Fig. 1: System setup: a) Transmitter, 320-km recirculating fiber loop and coherent optical receiver, b) 180-Gb/s differential electrical eye, c) optical spectrum after optical equalizer (OEQ).

The electrical signals within the multiplexing chain are decorrelated using RF cable delays that provide appropriate bit delays at 180 Gb/s. The shortest delay occurring within the 180-Gb/s multiplexed sequence is 37 bits, thus allowing for the use of a digital equalizer in the receiver with up to 36 symbol-rate spaced taps (72 taps at 2x oversampling). The differential amplitude of the 180-Gb/s waveform is ~500 mVpp and is applied to a dual-drive $LiNbO_3$ I/Q modulator with a measured 3-dB bandwidth of 37 GHz. Differential driving provides a cleaner and larger-amplitude signal in the absence of electrical driver amplifiers. Fig 2b shows a photograph of the final stages of the transmitter set-up with the outputs of the two selectors connected with short GPPO connectors to the modulator. Clock signals at 90 GHz are provided using passive frequency doublers, and the input clock amplitude is fixed near 300 mVpp. An external cavity laser (ECL) with a linewidth <100 kHz and 15-dBm output power is set to a wavelength of 193.4 THz and connected directly to the modulator with polarization maintaining (PM) fiber. An optical equalizing filter (OEQ) with a bandwidth of 200 GHz is applied at the output of the transmitter with an M-shape filter profile to assist with the bandwidth limitations of the system. The modulated optical spectrum after equalization is shown in Fig. 1c. Polarization multiplexing is achieved using a standard optical PDM emulator arrangement, where the delay is 18,386 symbols.

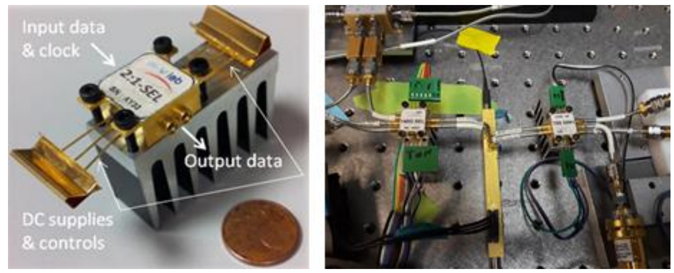

Fig 2: a) Photograph of packaged high-speed In-DHBT 2:1 selector (SEL). b) Photograph of the 180-GBaud QPSK transmitter using two InP-DHBT selectors and a dual drive I/Q $LiNbO_3$ modulator.

3. 180-Gbaud Transmission and Coherent Optical Detection

The 720-Gb/s line rate PDM-QPSK signal is input to a recirculating fiber loop for transmission as shown in Fig. 1. The loop consists of 80-km spans of standard single mode fiber (SSMF) with a dispersion of ~ 16ps/nm/km, and 4 spans are concatenated for a loop length of 320 km. Erbium doped fiber amplifiers (EDFA) are placed before each 80-km span, and the launch power into each span is controlled by an optical attenuator. The optimum launch power was set at 5 dBm. The transmitted signal is passed to a standard high-speed coherent intradyne receiver with a free-running ECL as LO, tuned to within ~200 MHz of the signal carrier. For back-to-back measurements, a noise loading stage is set to control the received optical signal-to-noise ratio (OSNR, 0.1-nm noise reference bandwidth). The signals are detected using a polarization-diversity 90-degree optical hybrid and balanced high speed InP wave-guide-integrated photodiodes with a measured 3-dB bandwidth of 100 GHz. The four outputs from the photo detectors are connected directly to four inputs on a Keysight real-time oscilloscope with >110-GHz bandwidth, sampling at 256 GS/s; multiple blocks of 1 to 5 million samples are taken for off-line digital signal processing. The off-line DSP performs receiver front-end corrections, resampling to two samples per symbol, timing recovery, a real-valued MIMO butterfly equalizer using adaptive tap updates based on the constant modulus algorithm (CMA), frequency offset compensation based on the fourth-power of the signal, and a blind phase search The CMA filter has 32 symbol-rate taps, shorter than the minimum pattern decorrelation delay of 37 bits, thereby preventing experimental artifacts.

4. Results

The back-to-back 180-Gbaud QPSK bit error ratio (BER) measurements as a function of received OSNR are shown in Fig. 3a for single-polarization and PDM. For a single polarization, the PDM emulator is bypassed and the input signal polarization to the receiver is adjusted to one polarization. We observe a similar performance for both polarizations, indicating that both the 100-GHz balanced photodiodes and the oscilloscope channels have similar performance characteristics. The PDM BER curve is shifted relative to the single-polarization curves by 3 dB, with no excess penalty due to PDM. We observe a BER floor of ~3×10^{-4} for both single-polarization (SP) and PDM, respectively. The required OSNR at the 7%-overhead hard decision (HD) forward error correction threshold (FEC) threshold of 3.8×10^{-3} is ~22 dB for SP and ~25 dB for PDM. The corresponding theoretical BER curves for 180-Gbaud QPSK SP and PDM are also shown. The implementation penalty relative to theory is ~ 4.7 dB for both SP and PDM. Representative DSP-recovered constellation diagrams for x and y polarizations at high OSNR are shown in Fig. 3

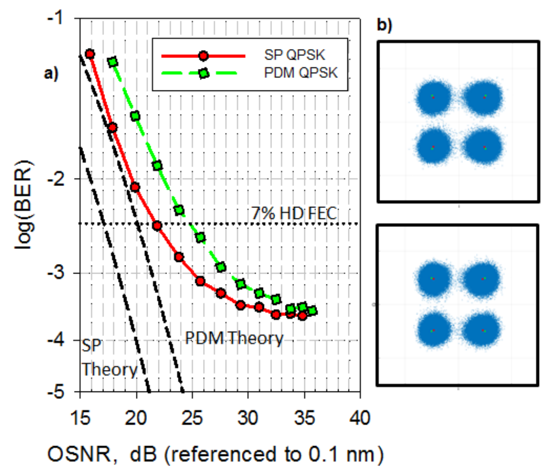

Fig. 3: a) Back to back BER vs OSNR for 180-GBaud QPSK. SP and PDM are shown. Dashed: 180-GBaud QPSK theory for SP and PDM and FEC threshold.
b) Constellations for each polarization at high OSNR

Figure 4 shows the transmission results. Both BER and normalized generalized mutual information (NGMI) [12] are plotted as a function of distance for the 180-Gbaud PDM-QPSK single-carrier system. At 4480 km, the NGMI is 0.878 which is above the NGMI threshold for an ideal SD FEC ideal NGMI of 0.861 [12]. The corresponding BER and OSNR at 4480 km is 3.31×10^{-2} and 20.9 dB. Transmission up to 1280-km is obtained assuming 7% overhead HDFEC. The corresponding capacity of the PDM channel is 673 Gb/s for HD FEC (7% overhead) and is reduced to 576 Gb/s for SD FEC (25% overhead).

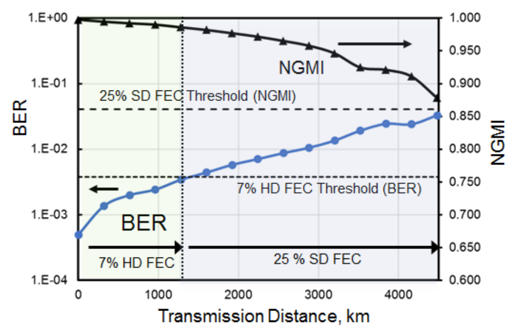

Fig. 4: BER and NGMI vs transmission distance for 180 Gbaud PDM-QPSK.

In conclusion, we demonstrated the first all-ETDM optical transmission system operating at 180 GBaud: a 30% improvement over the current all-ETDM record. Using PDM QPSK, we generate a line rate of 720 Gb/s on a single optical carrier and transmit over 4480 km of SSMF using EDFAs only. The system is enabled by new high-speed InP DHBT 2:1 selectors operating at 180 Gb/s, 100-GHz balanced photodetectors, and a real-time oscilloscope with 4 channels operating at >110 GHz and 256 GS/s.

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