All-ETDM 80-Gbaud (160-Gb/s) QPSK Generation and Coherent Detection

Gregory Raybon, Member, IEEE, Peter J. Winzer, Fellow, IEEE, Andrew A. Adamiecki, Alan H. Gnauck, Fellow, IEEE, Agnieszka Konczykowska, Filipe Jorge, Jean-Yves Dupuy, Member, IEEE, Larry L. Buhl, Christopher R. Doerr, Fellow, IEEE, Roger Delbue, and Peter J. Pupalaikis, Senior Member, IEEE

***Abstract*—A single-polarization 160-Gb/s (80-Gbaud) electronically time-division-multiplexed (ETDM) quadrature phase-shift-keyed (QPSK) signal is generated and coherently detected using two 45-GHz-bandwidth oscilloscope prototypes and offline processing.**

***Index Terms*—Coherent communications, fiber-optic links.**

I. Introduction

ADVANCES in the single-channel capacity of commercial optical systems have typically been achieved by increasing symbol rates to the highest rates supported by state-of-the-art optoelectronic modulation and detection hardware. Electronic time division multiplexing (ETDM) has been used to achieve binary modulation up to 100 GBaud, as demonstrated in several research experiments [1]–[3]; commercial deployments are using 40-GBaud modulation and direct detection [4]. Today, coherent detection combined with digital signal processing (DSP) provides an additional increase in single-channel bit rates through higher-order modulation and polarization-division multiplexing (PDM). Commercial coherent systems operate around 28 Gbaud, carrying 100-Gb/s payloads using PDM quadrature phase-shift-keying (PDM-QPSK).

The previous highest-symbol-rate coherent QPSK experiment using all-ETDM techniques was at 56 Gbaud; 224-Gb/s PDM-QPSK was enabled by two cotriggered 80-GSamples/s, 30-GHz-bandwidth oscilloscopes acting as analog-to-digital converters (ADCs) in the coherent receiver [5]. Here, we report all-ETDM 80-Gbaud single-carrier QPSK generation and coherent detection. Our single-polarization 160-Gb/s QPSK signal is generated using novel high-power 100-Gb/s indium phosphide heterostructure bipolar transistor (InP HBT) electronic multiplexers. Two cotriggered 120-GSamples/s oscilloscope prototypes, each supporting a single channel with 45-GHz bandwidth, make up the coherent receiver front-end.

Manuscript received May 20, 2011; revised August 03, 2011; accepted August 14, 2011. Date of current version October 21, 2011.

G. Raybon, P. J. Winzer, A. A. Adamiecki, A. H. Gnauck, L. L. Buhl, and C. R. Doerr are with the Alcatel-Lucent, Bell Laboratories in Holmdel, Holmdel, NJ 07733 USA (e-mail: greg.raybon@alcatel-lucent.com; Peter.winzer@alcatel-lucent.com; Andrew.adamiecki@alcatel-lucent.com; gnauck@alcatel-lucent.com; Larry.Buhl@alcatel-lucent.com; Christopher.Doerr@alcatel-lucent.com).

A. Konczykowska, F.Jorge, and J.-Y.Dupuy are with the III-V Laboratory, Bell Labs, Thales Research and Technology and CEA/LETI Joint Laboratory, F-01461, Marcoussis Cedex, France (e-mail: agnieszka.konczykowska@3-5lab.fr; filipe.jorge@3-5lab.fr; Jean-Yves.Dupuy@3-5lab.fr).

R. Delbue and P. J. Pupalaikis are with the LeCroy Corporation, Chestnut Ridge, NY 10977 USA (e-mail: Roger.Delbue@lecroy.com; Peter.Pupalaikis@lecroy.com).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2011.2166111

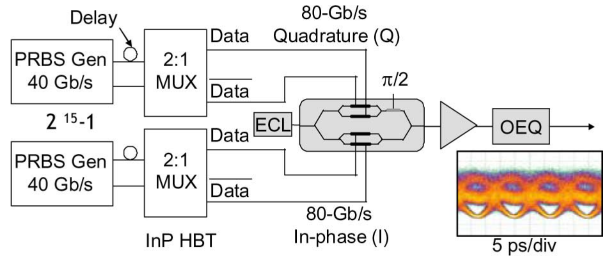

Fig. 1. 80-Gbaud (160-Gb/s) single-polarization QPSK transmitter. Inset: Optical QPSK eye diagram measured at $2^{15}-1$ PRBS length.

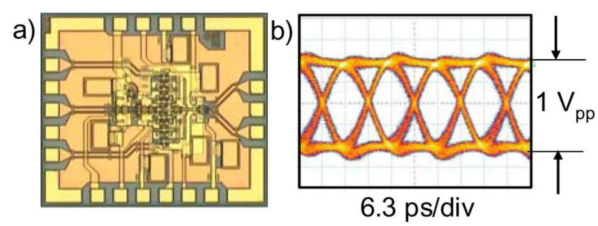

Fig. 2. (a) Microphotograph of the 2:1 InP HBT multiplexer; (b) electrical output eye diagram at 80 Gb/s for a PRBS $2^{15}-1$.

II. Experimental Setup

A. 80-Gbaud QPSK Transmitter

The transmitter setup is shown in Fig. 1. The in-phase (I) and quadrature (Q) 80-Gb/s bit sequences are realized by electrically multiplexing delay decorrelated $2^{15}-1$ 40-Gb/s pseudorandom bit sequences (PRBS) from two independent PRBS generators. The 2:1 multiplexers, fabricated using high-speed InP-HBT technology [6], provide $1-V_{\rm pp}$ signals from each of the differential outputs, thus providing a 2-Vpp differential drive. Fig. 2 shows a photograph of the chip and the measured electrical binary nonreturn-to-zero (NRZ) eye diagram from one of the outputs. The signal is applied to the respective I and Q arms of an integrated $LiNbO_3$ double-nested dual-drive Mach–Zehnder modulator without using driver amplifiers that could degrade the signal quality at these high data rates. The modulator modulates light from an external cavity laser (ECL) at 1550 nm with a linewidth of 5 kHz. We operate above the specified 3-dB bandwidth of the modulator (37 GHz) and below the optimal operating voltage swing $(2V_\pi = 7\ \text{V})$ and obtain an optical QPSK eye shown in Fig. 1, as measured on a high-speed sampling oscilloscope with 70-GHz bandwidth and a 100-GHz photodiode. We optionally pass the QPSK

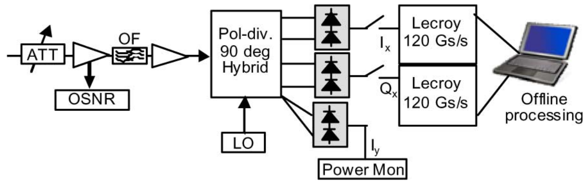

Fig. 3. Single-polarization coherent receiver based on two 120-GSamples/s oscilloscope prototypes with 45-GHz input bandwidth to individually detect the signal's two quadratures.

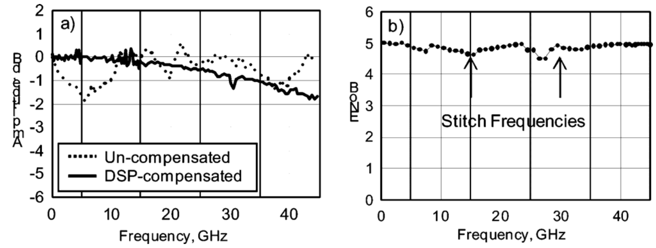

Fig. 4. (a) Amplitude response of the 45-GHz acquisition system before and after DBI processing. (b) ENoB measurement to 45 GHz.

signal through a single-chip planar lightwave optical equalizer (OEQ) with a 10-ps tap delay [7].

B. 80-Gbaud Coherent Intradyne Receiver

The coherent receiver (Fig. 3) consists of a two-stage Erbium-doped fiber amplifier (EDFA), with a variable optical attenuator (ATT) at the input to vary the received optical signal-to-noise ratio (OSNR). An optical filter (OF) with a bandwidth of 1.1 nm is used to reduce amplified spontaneous emission (ASE) noise. The signal is combined with a free-running ECL local oscillator (LO) of the same type as the signal laser in a polarization diversity 90° optical hybrid followed by balanced photodetection with 39-GHz bandwidth to detect both quadrature components of the single-polarization signal. Two LeCroy WaveMaster 8 Zi-A oscilloscope prototypes asynchronously sample and digitize the signal at 120 GSamples/s for subsequent offline DSP. One 45-GHz bandwidth channel is available per oscilloscope, thus requiring two cotriggered units to measure both quadratures (I_x, Q_x) of the desired signal polarization. The optical signal power in the other polarization (I_y) is monitored and manually minimized to assure full detection of the single-polarization signal. A full polarization-diversity receiver could be realized by adding two more 120-Gs/s oscilloscope inputs.

The high bandwidth and sampling rate of the scopes are obtained by digital bandwidth interleaving (DBI) [8]. In previous instruments, two 15-GHz channels were interleaved to provide a 30-GHz channel using DBI [5]. Here, three 20-GHz, 40-GSamples/s channels are combined with a microwave front-end and a DSP back-end. The input signal is split into three channels using a triplexer (a microwave filter that separates the incoming signal into three contiguous frequency bands). The mid and upper frequency bands are down-converted to frequencies that are appropriate for the ADCs, and all three channels are digitized, processed, and recombined by an embedded DSP algorithm. The most important element in the DSP is the magnitude and phase compensation. Fig. 4(a) shows the frequency response measurement for the full acquisition system before (dotted) and after (solid) DBI processing. The magnitude correction is achieved using infinite impulse response (IIR) filters and phase compensation through filters designed using inverse Fourier transform techniques. At 45 GHz, the compensated oscilloscope transfer function has rolled off by 2 dB. Fig. 4(b) plots the measured effective number of bits (ENoB) as a function of frequency. The variation of ENoB shows little deviation from 400 MHz out to 45 GHz. In particular, no noticeable glitches are observed at 15 and 30 GHz, where the three subspectra are stitched together by the DBI processing.

In order to capture the exact same time window on both scopes, as required to interpret the two captured signals as real and imaginary parts of the same optical waveform for further intradyne DSP, a high-speed trigger signal from a 50-Gb/s logic gate is applied to both instruments [5]. The small residual random skew between the two channels due to trigger timing jitter is compensated within the intradyne receiver algorithm by digitally inducing a correcting time shift on Q_x prior to forming the complex sample stream $I_x + jQ_x$. At 120 GSamples/s, the 80-Gbaud signal is oversampled by a factor of 1.5. Since the oscilloscope front-end acts as an anti-aliasing filter that limits the signal spectrum to <45-GHz, sampling at > 90 GSamples/s satisfies Nyquist's criterion. Nevertheless, the 45-GHz electrical filtering is equivalent to a sharp 90-GHz optical bandpass filter, and some penalty from tight filtering is expected. (For comparison, sharp filtering at 80/90–90% of the symbol rate was shown to result in an OSNR penalty between 1 and 3 dB [9], [10]).

After correcting for front-end skews, the offline intradyne receiver algorithm corrects for hybrid phase errors. It then oversamples a portion of the signal by a factor of 3 using zero-padding in the frequency domain and extracts the clock tone at the symbol rate $(1/T)$ from the spectrum of the magnitude-squared signal. Using the recovered clock, it synchronously upsamples the signal from 1.5 to 2. Using the constant-modulus algorithm (CMA) in combination with a 16-tap $T/2$-spaced single FIR filter (no butterfly structure is needed in our single-polarization experiment), the signal is adaptively equalized. Frequency and phase estimation use the Viterbi-Viterbi algorithm, followed by decision and differential decoding [5].

III. Results and Discussion

Fig. 5(a) shows back-to-back bit-error-ratio (BER) measurements for the 80-Gbaud (160-Gb/s) system as a function of the OSNR (0.1-nm reference bandwidth, taking into account both polarizations of the optical noise); data is plotted both for PRBS sequences of $2^{15} - 1$ (open triangles) and $2^7 - 1$ (open diamonds). At BERs below $\sim 2 \times 10^{-3}$, we see a noticeable pattern-dependent penalty that we attribute to the interplay between the strong linear filtering and the pattern-dependent output waveforms of the high-speed multiplexers, resulting in difficult to equalize intersymbol interference conditions. From the constellation diagrams shown in Fig. 5(b), we also observe slightly unequal spacings of the symbols in I and Q direction due to slightly unequal multiplexer output swings. The system is further limited by known 3-dB bandwidths of the optical modulator (37 GHz), the balanced photodiodes (39 GHz) and the front-end of the sampling oscilloscope (45 GHz), resulting in the need for substantial equalization at the band edge.

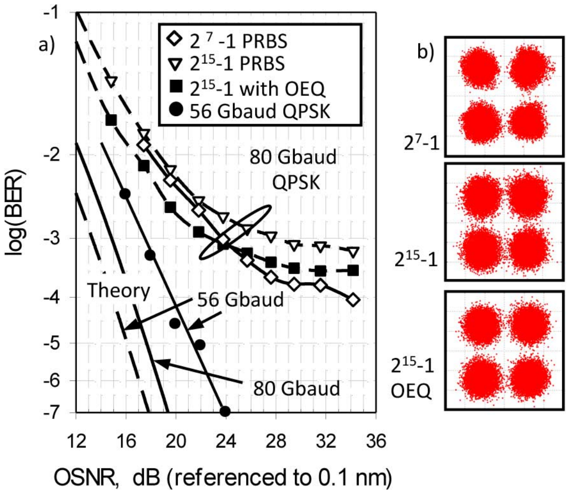

Fig. 5. (a) BER measurements for 80-Gbaud (160-Gb/s) QPSK with and without OEQ; 56-Gbaud data [5], [11] are shown as a reference. (b) Constellation diagrams for PRBS lengths of $2^7 - 1$ and $2^{15} - 1$, the latter with and without OEQ, all measured at an OSNR of 34 dB.

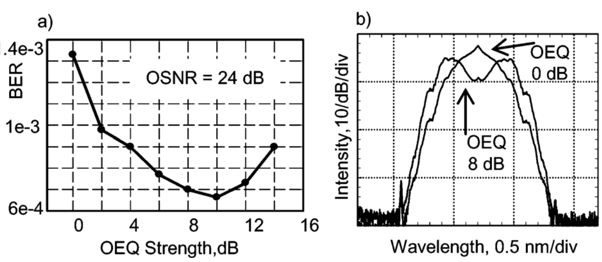

Fig. 6. (a) Optimization of OEQ at 24-dB OSNR. (b) Optical spectra for 8- and 0-dB OEQ, corresponding to BER and constellations of Fig. 5.

In order to avoid noise enhancement caused by receive-side equalization, we proceed to use pre-emphasis at the transmitter by means of an OEQ to improve the BER performance. Fig. 6(a) shows a plot of BER versus OEQ settings at a fixed OSNR of 24 dB ($2^{15} - 1$ PRBS). The horizontal scale quantifies the strength of optical equalization, as measured by the OEQ's maximum-to-minimum spectral transmission. The optical spectra for 8-dB and no (0-dB) optical equalization are shown in Fig. 6(b). Compared to the unequalized case, we clearly see a reduction in BER (~ 3 dB in OSNR at BER $= 2 \times 10^{-3}$) when using an optimum equalization near 8 dB. This brings the system performance to within 3 dB (at BER $= 2 \times 10^{-3}$) of the previously reported 56-Gbaud data (solid circles) [5], [11], leaving a ~ 6.0-dB implementation penalty at 80 GBaud. The theoretical curves for 56 and 80 GBaud are also shown as reference in Fig. 5(a). Recovered constellation diagrams for the cases with and without OEQ are also shown in Fig. 5(b), measured at an OSNR of 34 dB.

In order to compare the equalizing action of the transmit-side OEQ and the receive-side CMA-adapted digital FIR equalizer, Fig. 7 shows the transfer function of the fully adapted FIR equalizer for 4 different input signals, optically equalized by 0, 4, 8, and 12 dB. In the absence of OEQ, the digital equalizer boosts the band edges by about 10 dB. Other OEQ settings let the digital equalizer adapt to different filter shapes, maintaining a total of $\sim$10 dB of combined OEQ and DSP-based high-pass characteristics.

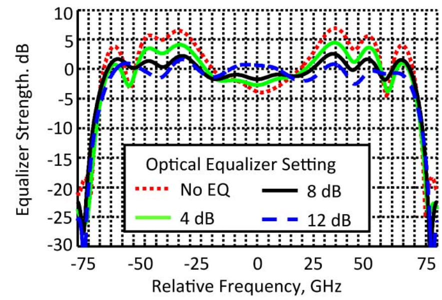

Fig. 7. DSP equalization strength for four different received optically equalized signals with varying OEQ settings.

IV. Conclusion

We have demonstrated the first 80-Gbaud all-ETDM coherent detection experiment, enabled through the use of high speed InP HBT multiplexers with high output voltage swing and 45-GHz real-time oscilloscope prototypes. This single-polarization experiment represents a first step toward realizing > 56-GBaud ETDM-based PDM-QPSK transmission. The Back-to-back BER measurements show a required OSNR of 20 dB at a BER of 2×10^{-3}, revealing a ~ 3.5-dB implementation penalty.

References

[1] P. J. Winzer, G. Raybon, C. R. Doerr, M. Duelk, and C. Dorrer, "107-Gbit/s optical signal generation using electronic time-division multiplexing," *J. Lightw. Technol.*, vol. 24, no. 8, pp. 3107–3113, Aug. 2006.

[2] G. Raybon, P. J. Winzer, and C. R. Doerr, "1-Tb/s (10×107 Gb/s) electronically multiplexed optical signal generation and WDM transmission," *J. Lightw. Technol.*, vol. 25, no. 1, pp. 233–238, Jan. 2007.

[3] A. Kanno, T. Sakamoto, A. Chiba, T. Kawanishi, M. Sudo, K. Higuma, and J. Ichikawa, "95 Gb/s NRZ-DPSK modulation with full-ETDM technique," in *Proc. Eur. Conf. Opt. Commun.*, Torino, Italy, 2010, Paper Mo.2.F.

[4] D. A. Fishman, W. A. Thompson, and L. Vallone, "LambdaXtreme® transport system: R&D of a high capacity system for low cost, ultra long haul DWDM transport," *Bell Labs Tech. J.*, vol. 11, pp. 27–53, 2006.

[5] A. H. Gnauck, P. Winzer, G. Raybon, M. Schnecker, and P. J. Pupalaikis, "10×224-Gb/s WDM transmission of 56-Gbaud PDM-QPSK signals over 1890 km of fiber," *IEEE Photon. Technol. Lett.*, vol. 22, no. 13, pp. 954–956, Jul. 1, 2010.

[6] J. Godin, V. Nodjiadjim, M. Riet, P. Berdaguer, O. Drisse, E. Derouin, A. Konczykowska, J. Moulu, J.-Y. Dupuy, F. Jorge, J.-L. Gentner, and A. Scavennec, "Submicron InP DHBT technology for high-speed high-swing mixed-signal ICs," in *Proc. CSICS*, Monterey, CA, 2008, pp. 109–112.

[7] C. R. Doerr, P. Winzer, G. Raybon, L. L. Buhl, M. A. Cappuzzo, A. Wong-Foy, Y. K. Chen, L. T. Gomez, and M. Duelk, "A single-chip optical equalizer enabling high-fidelity 107- Gb/s optical nonreturn-to-zero signal generation," in *Proc. Eur. Conf. Opt. Commun.*, Glasgow, Scotland, 2005, Paper PD 4.2.1.

[8] P. J. Pupalaikis and M. Schnecker, "A 30 GHz bandwidth, 80 GS/s sample rate real-time waveform digitizing system," in *Proc. OFC/NFOEC*, Los Angeles, CA, 2010, Paper JThA52.

[9] C. R. S. Fludger *et al.*, "Coherent equalization and POLMUX-RZ-DQPSK for robust 100-GE transmission," *J. Lightw. Technol.*, vol. 26, no. 1, pp. 64–72, Jan. 1, 2008.

[10] P. J. Winzer, A. H. Gnauck, C. R. Doerr, M. Magarini, and L. L. Buhl, "Spectrally efficient long-haul optical networking using 112-Gb/s polarization-multiplexed 16-QAM," *J. Lightw. Technol.*, vol. 28, no. 4, pp. 547–556, Feb. 15, 2010.

[11] P. J. Winzer, A. H. Gnauck, G. Raybon, P. J. Pupalaikis, and M. Schnecker, "56-Gbaud PDM-QPSK: Coherent detection and 2,500-km transmission," in *Proc. Eur. Conf. Opt. Commun.*, Vienna, Austria, 2009, Paper PD 2.7.