# 56-Gbaud PDM-QPSK: Coherent Detection and 2,500-km Transmission

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**Abstract** *A 56-Gbaud (224-Gb/s line rate) polarization-division multiplexed quadrature phase shift keyed (PDM-QPSK) signal is transmitted over 2,500 km (32 x 80 km) of fiber and is coherently detected using an 80-GSamples/s oscilloscope with off-line signal processing.*

## Introduction

With 100-Gb/s transport technologies getting close to commercialization, research is focusing on scaling per-channel bit rates beyond 100 Gb/s, with the goal to develop spectrally efficient solutions for the next Ethernet standards, likely at 400 Gb/s and 1 Tb/s. Approaches include orthogonal sub-carrier multiplexing[1] and single-carrier multilevel modulation at high symbol rates[2,3]. The latter method allows for a simpler transmitter structure at approximately equal receiver and digital signal processing hardware[4]. Single-polarization quadrature phase shift keying (QPSK) at 53.5 Gbaud and binary modulation at 107 Gbaud have been demonstrated[5] using direct detection; the lack of sufficiently fast analog-to-digital converters (ADCs) has prevented coherent detection without resorting to optical time division demultiplexing[6] (OTDM), which severely complicates digital compensation of impairments with memory, such as chromatic dispersion (CD). The highest coherently detected symbol rate without OTDM today is[7] 28 Gbaud for QPSK and 20 Gbaud for 16-QAM[2,3].

In this paper, we report the generation, coherent demodulation, and long-haul transmission of 56-Gbaud polarization-division multiplexed (PDM) QPSK, yielding a single-channel line rate of 224 Gb/s.

## 56-Gbaud PDM-QPSK Transmitter

The experimental setup is shown in Fig. 1. A tunable external-cavity laser (ECL) at 1550 nm with ~100 kHz linewidth is modulated using an integrated $LiNbO_3$ double-nested Mach-Zehnder modulator with 25-GHz 3-dB bandwidth and 4 $V_\pi$. The in-phase (I) and quadrature (Q) branches of the modulator are differentially driven by two 56-Gb/s binary electrical sequences. These are generated by 4:1 multiplexing four delay-decorrelated copies of a 14-Gb/s true pseudo-random bit sequence (PRBS) of length $2^{15}$–1. Polarization multiplexing is achieved by 3-dB splitting the 56-Gbaud QPSK signal, delaying one copy by 20 ns (1,120 symbols), and combining them in a polarization beamsplitter (PBS), using manual polarization controllers (PCs). The delay is adjusted such that the symbols in the two polarizations are aligned. Eye diagrams and optical spectrum of the 56-Gbaud QPSK signal are shown in the inset to Fig. 1.

## 56-Gbaud Coherent Intradyne Receiver

At the receiver, the signal is combined with an ECL local oscillator (LO) in a polarization-diversity 90-degree hybrid, followed by 4 balanced detectors. The free-running LO is tuned to within ±1 GHz of the signal carrier. The 4 signal components ($I_x$, $Q_x$, $I_y$, $Q_y$) are asynchronously sampled and digitized using as ADCs 2 two-channel 80-GSamples/s real-time scopes with 30-GHz bandwidths; the frequency response is given in Fig. 2. The high bandwidth and sampling rate are based on digital bandwidth interleaving[8] (DBI). The effective number of bits (ENoB) is > 4.5.

To capture the exact same time window on both scopes, as required for intradyne signal processing, a high-speed trigger signal from a 50-Gb/s logic gate is applied to both instruments. We characterized the residual timing skews by simultaneously sampling a

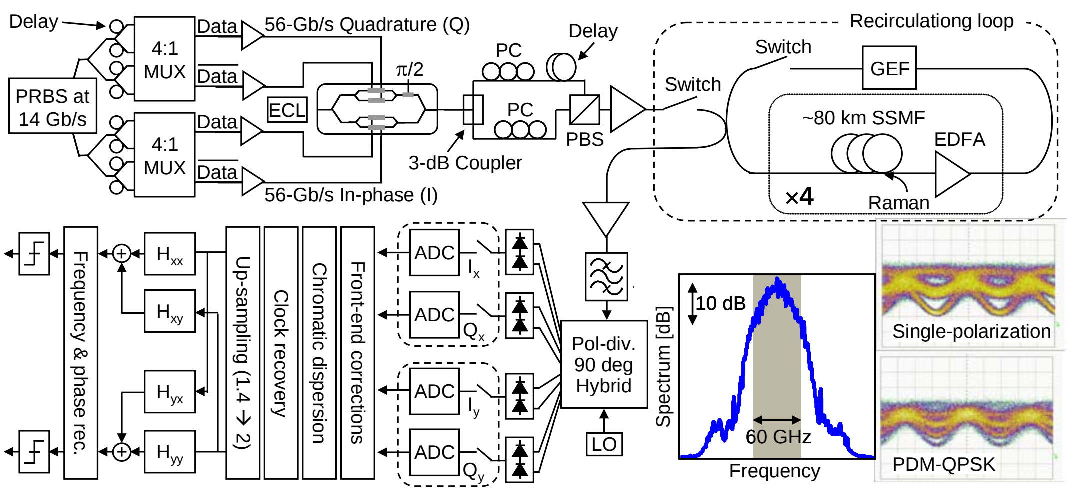


**Fig. 1:** Experimental setup of 224-Gb/s PDM-QPSK transmitter and coherent receiver. *Inset:* Optical spectrum and eyes.

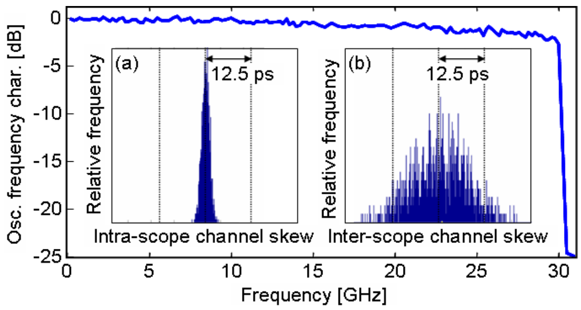


**Fig. 2:** Oscilloscope frequency response. *Insets:* Histograms of timing skews within scope (a) and between scopes (b).

fast reference signal. The inset to Fig. 2 shows histograms of ~1000 measurements for the skew *within* a scope (a) and *between* the two scopes (b). The intra-scope skew standard deviation is ~1 ps, and the inter-scope skew can be as large as ± 1.5 samples (± 19 ps). Both random skews are readily compensated within the intradyne receiver algorithm.

As for the sampling rate, we note that the 80-GSamples/s ADCs oversample the 56-Gbaud signals only by a factor of 1.4. Since the oscilloscope front-end acts as an anti-aliasing filter that limits the signal spectrum to < 30 GHz, sampling at > 60 GSamples/s satisfies Nyquist's criterion. (This process is equivalent to filtering the 56-Gbaud optical signal with a 60-GHz wide optical filter, followed by twofold oversampling at 112 GSamples/s. A 60-GHz window is shown in relation to the signal spectrum in Fig. 1.)

A block diagram of the intradyne receiver algorithm is shown in Fig. 1. We first correct for front-end imperfections, e.g., sampling skew and hybrid phase errors. We then perform CD compensation in the frequency domain. The subsequent clock recovery oversamples a portion of the signal by a factor of 3 using zero-padding in the frequency domain and extracts the tone at the symbol rate (1/T) from the spectrum of the magnitude-squared signal. Using the recovered clock, we synchronously upsample the signal from 1.4 to 2.

Blind source separation, adaptive equalization, and timing recovery are done by a butterfly filter with 16-tap T/2-spaced FIR filters ($H_{xx}$, $H_{xy}$, $H_{yx}$, $H_{yy}$) using the constant-modulus algorithm. Frequency and phase estimation are done by the Viterbi-Viterbi algorithm,

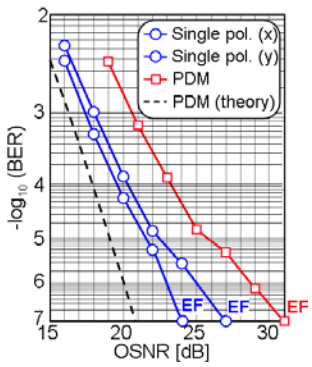


**Fig. 3:** BER performance at 56 Gbaud: Single-polarization 112-Gb/s QPSK and 224-Gb/s PDM-QPSK.

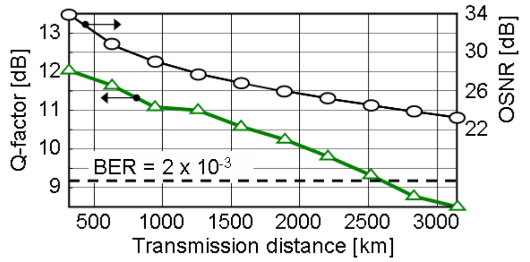


**Fig. 4:** Transmission performance (Q-factor, triangles) and delivered OSNR (circles) vs. transmission distance.

followed by decision and differential decoding[7].

### Back-to-back Characterization

Figure 3 shows the back-to-back bit error ratio (BER) vs. optical signal-to-noise ratio (OSNR, 0.1-nm reference bandwidth, noise in both polarizations). The circles represent single-polarization 112-Gb/s QPSK signals with a ~0.5-dB difference between x and y polarization due to front-end imperfections. The 224-Gb/s PDM-QPSK signal (squares) has no excess PDM penalty and exhibits a sensitivity of ~20.5 dB at BER = $10^{-3}$, ~4 dB off the theoretical limit (dashed). All measurements were error-free (EF) at high enough OSNR (within the statistical limits of ~2.5 million bits used to calculate the BER from 1 million recorded samples per polarization and quadrature).

### Transmission over 2,500 km of Fiber

Single-channel 56-Gbaud PDM-QPSK transmission was performed in a recirculating loop (Fig. 1) of four ~80-km standard single-mode fiber spans (SSMF, 16 to 17 dB loss/span, 315-km loop length), a gain-equalizing filter (GEF), and no in-line dispersion compensation. Backward Raman amplification (10-dB net gain) and EDFAs with ~5-dB noise figures were used. The signal launch power was -2 dBm, which we found to be close to optimum up to 3000 km.

Triangles in Fig. 4 represent the BER (as Q-factor) versus transmission distance. With a forward error correction (FEC) threshold of 2 x $10^{-3}$, 2,500 km can be bridged. Cirlces give the delivered OSNR, showing ~2.5-dB transmission penalty at 2,500 km.

### Conclusions

We have demonstrated the first 56-Gbaud coherent detection experiment with full digital impairment compensation. Our 224-Gb/s PDM-QPSK signal has a back-to-back OSNR sensitivity of 20.5 dB and can be transmitted over 2,500 km at BER < 2 x $10^{-3}$.

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