# Long-haul coherent QPSK transmission of 40G channels with 120% spectral efficiency using increased linearity dispersion map with 100km spans and EDFAs

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**Abstract**: We study transmission of 40 Gb/s signals using coherent RZ-QPSK with and without polarization multiplexing using 100km large effective area fiber-spans and dual-stage EDFAs with mid-stage dispersion compensation. We show advantage and disadvantage of coherent detection schemes.

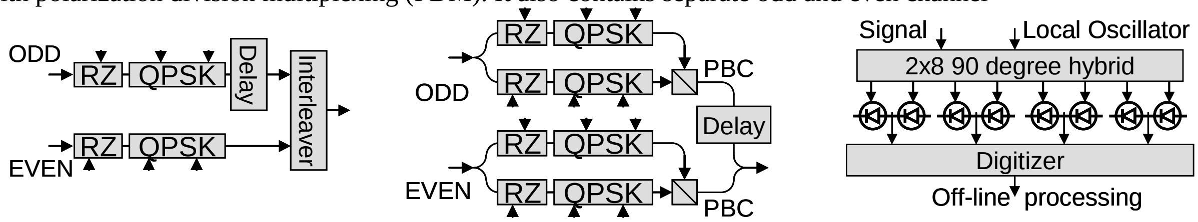
**OCIS codes**: (060.2330) fiber optics communications; (060.1660) Coherent communications

## 1. Introduction

High spectral efficiency is particularly difficult to achieve in multiple-thousand km length cable systems. This is especially true for a spectral efficiency greater than 100%. In addition to the noise limited performance, long-haul systems are impaired by the non-linear transmission properties of the fiber. In previous experiments over transoceanic distance spectral efficiency of 80% was demonstrated using coherent PDM-BPSK [1]. Later 200% and 370% were achieved using coherent PDM-QPSK and PDM-OFDM-QPSK [2-4]. Distributed Raman amplification was used in these high spectral efficiency experiments to reduce noise accumulation and extend transmission distance. In our work we have investigated 40 Gb/s transmission with coherent receiver using single polarization 20 Gbaud and polarization multiplexed 10 Gbaud RZ-QPSK carriers launched at 33 GHz frequency spacing. We have demonstrated spectral efficiency of 120% over a distance of 7200 km using an "EDFA only" amplifier chain with 100 km large effective area fiber spans. Dispersion management was done by placing dispersion compensating modules in between the stages of dual-stage amplifier. This configuration is similar to that commonly used in terrestrial systems and it improves system noise performance and linearity [5] relative to more traditional fiber spans with positive and negative dispersion slope compensating fibers. We tested the performance of the coherent receiver with absolute phase detection without differential coding (QPSK) and with differential coding (DC-QPSK), and differential phase detection (DQPSK). Using the absolute phase detection scheme without differential coding, i.e. QPSK, the achieved performance was near theoretical OSNR sensitivity limit. However this scheme may suffer from cycle slips induced by accumulated signal phase wandering discussed in details in [6]. The use of differential schemes, i.e. DC-QPSK and DQPSK, allows to avoid the cycle slip problem with a price of receiver sensitivity degradation [7]. We have found that the coherent DQPSK receiver provides the lowest OSNR sensitivity but the best nonlinear tolerance, which confirmed precious simulation results in [8].

## 2. Experimental Setup

Fig. 1(a-c) shows the schematics of the 40G coherent RZ-QPSK experiment. Single polarization 23 Gbaud transmitter consists of two pre-filtered and orthogonally combined modulation paths; even channels go through one, odd through the other (Fig 1a). Pre-filtering and orthogonal combining are performed simultaneously using a 33 GHz optical interleaving filter. The single polarization RZ-QPSK signals are created using a combination of I&Q data modulator and MZ modulator for the RZ. The two modulation paths are operated with $2^{23}$-1 data and inverted data patterns at 23 Gbaud, corresponding to a 15% FEC rate. Fig 1b displays 11.5 Gbaud RZ-QPSK transmitter with polarization division multiplexing (PDM). It also contains separate odd and even channel




a). b). c).

Fig 1. Schematic of single polarization RZ-QPSK transmitter at 23 Gbaud (a), Polarization multiplexed RZ-QPSK transmitter at 11.5 Gbaud (b), and coherent receiver (c).

modulation paths. 40 Gb/s channel is generated by splitting a single wavelength into two modulation paths driven at a symbol rate of 11.5 Gbaud with a quarter word shift in the $2^{23}$-1 PRBS patterns and subsequent orthogonal optical combining. The symbol rate included 15% FEC overhead. The digital coherent receiver shown in Fig 1c [9] is based on data acquisition with a real time oscilloscope and subsequent off-line post processing [10-11]. The local oscillator (LO) operated in a free run mode. Prior to the receiver the channels were separated using another 33 GHz optical interleaving filter as well as a wide-band tunable filter.

The loop test bed consisted of six 100 km amplifier-spans. Each hybrid span had 50 km positive dispersion, large effective area fiber ~135 $\mu m^2$ followed by 50 km of pure silica core fiber. The accumulated dispersion was compensated by placing ~9 km DCF modules providing approximately –2300 ps/nm between stages of a 28nm dual-stage EDFAs (See Fig. 2) similar to [12]. Such configuration provided about ~ 1 dB of noise performance advantage relative to regular dispersion managed spans with negative dispersion fiber being a part of the transmission span. The average launch-power into the transmission spans was approximately +20.5 dBm.

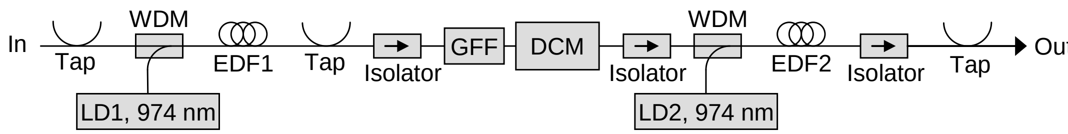



Fig 2. Schematic of the dual-stage EDFA with mid-stage dispersion compensating module DCM.

The transmission line was loaded with CW DFB lasers, and the measurement region was replaced with eight ECL lasers to take advantage of the ECL's narrow line-width and ability to be tuned to arbitrary wavelengths. Among the 8 ECL lasers, the performance of the four center channels was measured and the wavelength of all eight ECL lasers was shifted to the next measurement region [13, 14].

### 3. Coherent Receiver Algorithms

We performed the necessary digital signal processing off-line. The carrier phase estimation (CPE) was performed with a decision feedback algorithm and the Viterbi-Viterbi (the $M^{th}$ power) algorithm [15], respectively, for the QPSK and DC-QPSK schemes. In addition to the absolute phase detection schemes we also investigated the coherent DQPSK scheme that does not require CPE. A constant modulus algorithm (CMA) with 5-taps was used for polarization tracking and PMD compensation. The receiver's dispersion compensation was performed digitally in the off-line processing suite of algorithms.

### 4. Results

Fig. 3 shows the Q-factor as a function of received OSNR measured back-to-back for single polarization 23 Gbaud QPSK and polarization multiplexed 11.5 Gbaud DC-QPSK as well as theoretical limits for QPSK and DC-QPSK. Performance of DC-QPSK is ~1dB lower at low OSNR compared to QPSK. However this difference gradually disappears with the increase of OSNR. Measured performance of both 11.5 and 23 Gbaud rates obtained with and without differential coding is close to theoretical predictions [7]. Performance obtained with noncoherent differential phase detection (DQPSK) is also included for comparison and is more than 2 dB lower than that of coherent detection.

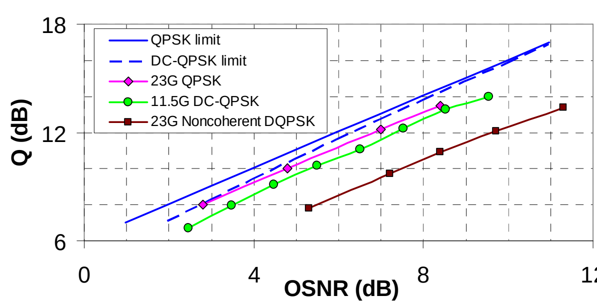



Fig 3. Back-to-back performance (OSNR in 0.4 nm RBW). Theoretical limits for coherent QPSK (solid line) and DC-QPSK (dashed line). Measured QPSK at 23 Gbaud (diamond symbols), DC-QPSK at 11.5 Gbaud dual polarization (round symbols), and noncoherent DQPSK at 23 Gbaud (square symbols).

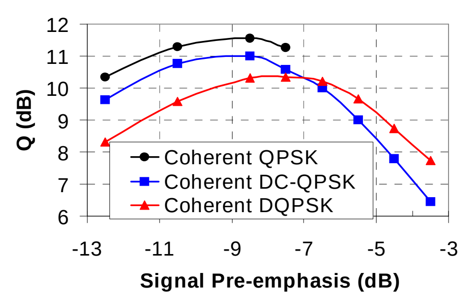



Fig 4. Power pre emphasis sweep for 23 Gbaud single polarization channel at ~1550 nm after 4.2 Mm distance with coherent QPSK (round symbols), coherent DC-QPSK (square symbols), and coherent DQPSK (triangle symbols).

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The coherent QPSK scheme provides the best performance after 4.2 Mm transmission compared to the other schemes (Fig. 4). From Fig. 4 it also follows that the coherent DQPSK scheme provides a better nonlinear tolerance, which agrees well with previous simulation results [8]. At high signal powers the coherent QPSK scheme suffers from loss of phase tracking [6].

Figure 5 shows the measured performance after the propagation in the loop testbed as a function of distance. Near 4.2 Mm coherent detection gave a 2 dB advantage relative to intensity detection. However this benefit reduces as the distance approaches 6 Mm. The polarization multiplexed coherent DC-QPSK at 11.5 Gbaud offers the best performance.

Fig. 6 shows Q-factor for three groups of channels in PDM-RZ-QPSK experiments at 11.5 Gbaud using the coherent DC-QPSK or coherent DQPSK scheme. At short distance DC-QPSK outperforms DQPSK, while at 10 Mm distance DQPSK provides better performance indicating that it is more tolerant to increased nonlinearity.

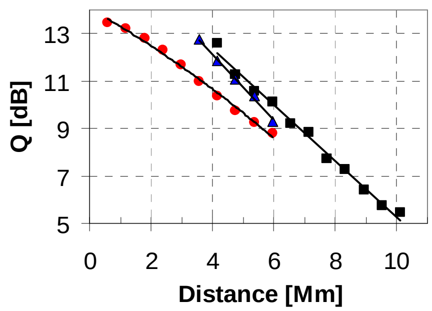


Fig 5. Performance vs. distance for channel at ~1550 nm. Square symbols: 11.5 Gbaud Pol. Mux. coherent DC-QPSK; triangles: 23 Gbaud single polarization coherent DC-QPSK round symbols: 23 Gbaud noncoherent DQPSK.

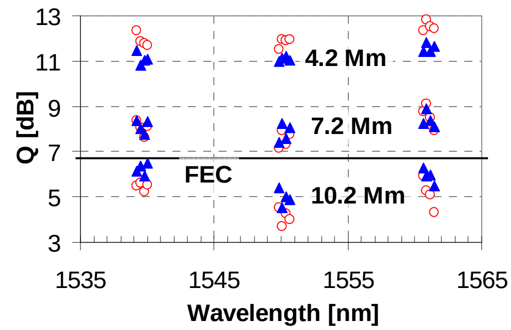


Fig 6. Q-factor for 4.2, 7.2 and 10.2 Mm distance with coherent DC-QPSK (round symbols) and coherent DQPSK (triangle symbols).

## 5. Conclusions

We demonstrated back-to-back performance close to theoretical predictions using 10 and 23 Gbaud RZ-QPSK transmitter and coherent receiver. Using 11.5 Gbaud polarization multiplexed RZ-QPSK format we show 40 Gb/s transmission over 7,200 km with 120% spectral efficiency and 100km repeater spacing using, a linear dispersion-managed transmission line. The use of either differential phase detection (DQPSK) or differential coding (DC-QPSK) eliminated detrimental effect of phase slips present with absolute phase detection in digital processing and allowed to achieve ~0.7 dB of Q-factor margin on selected groups of channels across the bandwidth.

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