40 Gb/s Transmission Using a Hybrid PDM Technique

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Abstract: A hybrid polarization division multiplexing (PDM) technique was demonstrated for 40Gb/s RZ-DPSK signal without polarization tracking receiver (PTR). Long-term Q-factor measurements and DGD tolerance study showed performance similar to offset PDM and regular PDM with PTR.

OCIS codes: (060.2330) fiber optics communications; (060.4230) multiplexing; (060.5060) phase modulation

1. Introduction

Polarization division multiplexing (PDM) techniques have been widely investigated to double spectral efficiency and to enhance dispersion and nonlinear tolerance thanks to the half symbol rate [1-3]. Unfortunately, to demultiplex the two polarization tributaries, an automatic polarization tracking receiver (PTR) with endless rotation and reset-free operation is required for conventional incoherent receivers. Besides added complications and system cost, the automatic PTR is also prone to weak tracking and loss of control due to the potential existence of "dead spot" [4]. Therefore, PDM demultiplexing without PTR is also preferred even for incoherent detection. We proposed and demonstrated offset PDM [5] which combines two orthogonal channel separated by ¼ FSR offset and showed that offset PDM (without PTR) performed similar to regular PDM with PTR.

In this paper, we report a new "hybrid" multiplexing technique that does not require an automatic PTR and eliminates the requirement of having a frequency offset for the two polarizations. By orthogonally multiplexing RZ-DPSK and $\pi/2$ RZ-DPSK at the same wavelength, hybrid PDM occupies the same spectral space as regular RZ-DPSK. At the receiver, the demultiplexing (rejection of orthogonal polarization) and detection were achieved with a pair of DPSK receivers. This new hybrid PDM scheme eliminates the need for a polarization tracking receiver by nulling out the $\pi/2$ RZ-DPSK signal at the RZ-DPSK receiver and vice versa.

The performance of hybrid PDM was compared with that of incoherent offset PDM and regular PDM over 5,200 km with 60% SE and 150 km repeater spacing. Hybrid PDM performed similar to offset PDM, and showed better PMD tolerance compared to offset PDM and regular PDM. Furthermore, the long term Q-factor histogram shows the effectiveness of our polarization demultiplexing technique (without automatic PTR) in the presence of time varying polarization effects including signal SOP, link's principal state of polarization (PSP), accumulated polarization dependent losses (PDL), and PMD.

2. Experimental setup

Fig. 1a shows the schematic of the 40 Gb/s hybrid PDM RZ-DPSK transmitter. The transmitter consisted of a RZ modulator, PM 3-dB coupler, DPSK modulator, $\pi/2$ DPSK modulator (that includes a MZ intensity modulator and a 90^0 phase modulator), a PM phase shifter, and a polarization beam combiner (PBC). The DPSK & $\pi/2$ DPSK modulators were driven by two 23 Gb/s (with 15% FEC overhead), pre-coded 2^{31}-1 PRBS, with a ½ word delay. The pre-coding function for $\pi/2$ DPSK was different from that for DPSK. The phase shifter was set so that there was a ½ bit delay (21.7 ps) between the two polarization tributaries at the output of the PBC.

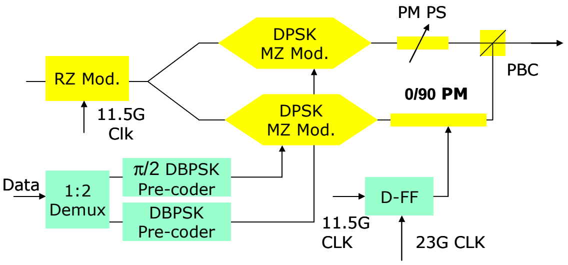

Fig. 1a: 46Gb/s hybrid PDM RZ-DPSK transmitter
PBC: Polarization Beam Combiner, PS: Phase Shifter

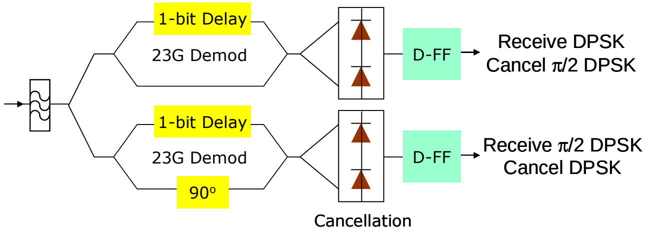

Fig. 1b: 46Gb/s hybrid PDM RZ-DPSK receiver
(No automatic PTR is needed for polarization demultiplexing)

The performance of the hybrid PDM RZ-DPSK was compared with regular PDM and offset PDM RZ-DPSK formats in a long repeater spacing system experiment using the same circulating loop test-bed as in our previous work [5]. Here, 50 x 40 Gb/s WDM signals were combined in a 66.6 GHz optical interleaving filter to produce a spectral efficiency of 0.6 bit/s/Hz. A common fast polarization scrambler was inserted before the pre-compensation section to suppress the PDL effect. This would not be feasible for the conventional PDM as polarization tracking would be severely compromised. The 1,040 km loop test bed consisted of 7 hybrid ROPA/EDFA spans each 150-km long. The spans were symmetrically built using a 1:1:1 combination of SLA fiber (110 um^2, + 20ps/nm/km), IDF fiber (30 um^2, -40ps/nm/km), and SLA fiber. After 950 ps/nm of pre-compensation, the WDM signals were launched into the test bed and circulated 5 times to reach 5,200 km distance. More details of the loop testbed and ROPA EDFA can be found in [7, 8].

In the receiver, the RZ-DPSK demodulator is used to demodulate the RZ-DPSK signal and nulls out the π/2 RZ-DPSK signal and vice versa. The π/2 RZ-DPSK receiver is similar to the RZ-DPSK receiver except for the 90^0 phase offset in the demodulator.

3. π/2 RZ-DPSK and Hybrid PDM RZ-DPSK

The π/2 RZ-DPSK is generated by the cascading the RZ modulator, 90^0 phase modulator and a DPSK modulator. The RZ modulator and 90^0 phase modulator generated a pulse train with alternating phase (0^0 or 90^0). The 0/90^0 pulse train was phase modulated with the DPSK modulator. As a result, the phase difference between any two adjacent bits is 90^0 or -90^0. In the receiver, a 90^0 phase shift was introduced in one of the demodulator arms to achieve constructive or destructive interference at the demodulator output. Data was pre-coded at the transmitter to ensure that the decoded bits at receiver were indeed a PRBS pattern.

In the receiver, RZ-DPSK and π/2 RZ-DPSK were received separately for hybrid PDM-DPSK. For the π/2 RZ-DPSK receiver, the demodulator was optimized with a 90^0 phase shift, hence π/2 RZ-DPSK is demodulated (Fig 1a). For the RZ-DPSK modulated polarization tributary, the 90^0 phase shift produced incoherent summation of two neighboring bits on both the constructive and destructive ports of the π/2 RZ-DPSK demodulator, and was canceled out by the balanced receiver as shown in Fig. 2b. Similarly, π/2 RZ-DPSK was cancelled from RZ-DPSK receiver due to the lack of 90^0 phase shift in the the RZ-DPSK demodulator.

Fig. 2c & 2d show the received eye diagram from π/2 RZ-DPSK receiver when the two polarization tributaries were bit-interleaved and bit-aligned, respectively. Similar to offset PDM, bit-interleaving case provides 3-dB benefit compared to bit-aligned case mainly due to the reduced impact from signal-spontaneous beat noise from orthogonal tributary. Furthermore, interleaving the polarization tributaries at the transmitter reduces nonlinear penalty [3]. There is ~1.5dB extra benefit from bit-interleaving after 5200 km transmission due to reduced cross phase modulation.

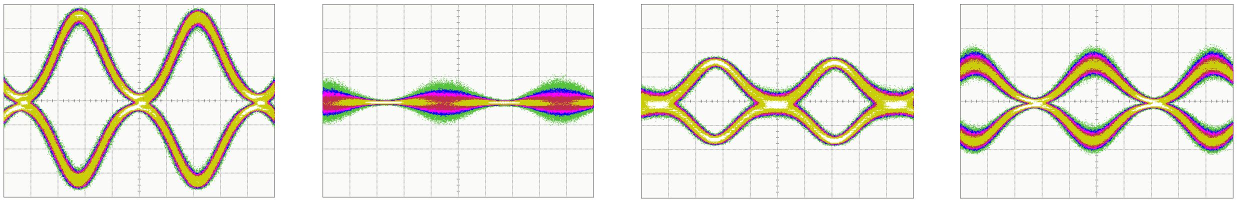
a: only π/2 RZ-DPSK
b: only RZ-DPSK
c: bit interleaved
d: bit aligned

Fig. 2: Eye diagrams from π/2 RZ-DPSK receiver

Hybrid PDM RZ-DPSK multiplexes RZ-DPSK and π/2 RZ-DPSK at the same wavelength. Hence, the optical spectral width of hybrid PDM is smaller than that of offset PDM, therefore hybrid PDM offers potentially higher spectral efficiency and higher DGD tolerance than offset PDM. Fig. 3 compares the back-to-back DGD tolerance for RZ-DPSK, π/2 RZ-DPSK, hybrid PDM, and offset PDM. First, similar DGD tolerance was measured for RZ-DPSK and π/2 RZ-DPSK, probably due to the same optical bandwidth. Second, both PDM schemes suffered DGD induced penalty due to non-perfect bit-interleaving because of DGD. Finally, Hybrid PDM had better DGD tolerance compared to offset PDM due to the narrow optical spectrum.

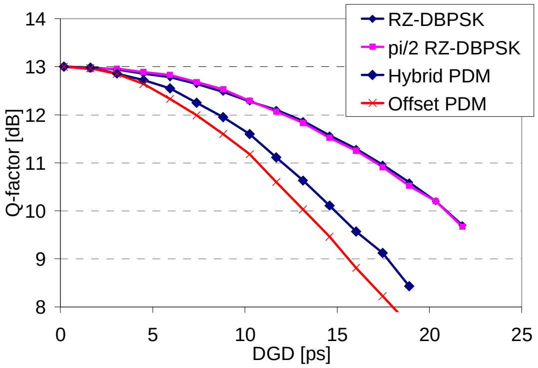

Fig. 3: DGD tolerance for offset and hybrid PDM RZ-DPSK modulation format.

4. Hybrid PDM RZ-DPSK transmission over 5,200 km with 150 km repeater spacing and 60% SE

Fig. 4a shows the performance vs. channel power for 40 Gb/s regular, offset, and hybrid PDM RZ-DPSK modulation formats, measured with the same testbed and under the same conditions (50x40 Gb/s over 5,200 km with 150 km repeater spacing and 66.7 GHz channel spacing). Hybrid PDM was actually measured at a line rate of 46G while offset and regular PDM were measured at 42.7G. The details of the 40 Gb/s regular PDM RZ-DPSK with automatic PTR can be found in [3], and the details of the 40Gb/s offset PDM RZ-DPSK can be found in [5]. The performance of the two polarization tributaries was measured with the same transmitter settings, the same receiving filter setting and the same pre- and post- dispersion compensation. Automatic polarization scanners at the transmitter and a continuous LSPC were used in all experiments; therefore time varying polarization effects and interactions between nonlinearity and PDL/PMD were all captured in all measurements. The Q-factor difference between the two polarization tributaries was <0.5 dB for all PDM formats, so only the average Q-factors (BER average) are reported in Fig. 4a.

RZ-DPSK and π/2 RZ-DPSK polarization tributary showed similar performance as shown in Fig. 4a. Therefore RZ-DPSK and π/2 RZ-DPSK had the same nonlinear tolerance. Hybrid PDM performed similar to 23G ¼R offset PDM. The 23G ¼R offset PDM results are shown with a 0.3dB down-shift from the 21.3G measurement [5] to account for the increased line rate.

Fig. 4b compared the long-term Q-factor distributions for regular PDM [3], offset PDM [5], and hybrid PDM. There were ~1 million BER samples measured for offset PDM, ~ ½ million from RZ-DPSK, and ~ ½ million from π/2 RZ-DPSK. Please also note that hybrid PDM was measured at 23Gb/s, which induced ~0.3dB Q-factor penalty compared with 21.3Gb/s (both regular and offset PDM measured at 21.3Gb/s). Although both offset and hybrid PDM performed slightly worse (on average) than regular PDM, the Q-factor @ 1e-6 probability was slightly better than that for regular PDM. Comparing hybrid PDM with offset PDM (taking away the 0.3dB linear difference from the bit rate), hybrid PDM performed slightly better than offset PDM. Therefore, we conclude that the performance of hybrid PDM is better than both offset PDM and regular PDM with automatic PTR.

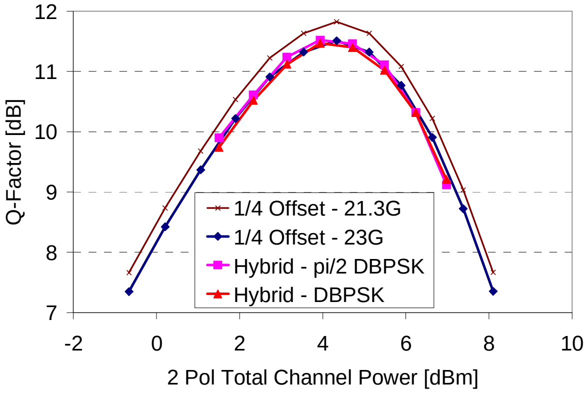

Fig. 4a: Performance comparison for regular, offset, and hybrid PDM RZ-DPSK modulation formats after 5,200 km. From 21.3G to 23G, there is ~0.3dB Q-factor penalty

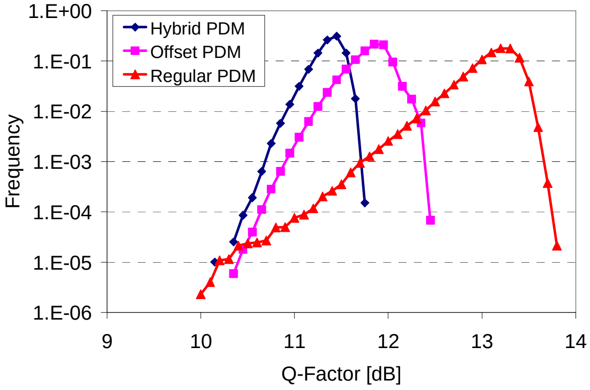

Fig. 4b: Long term Q-factor distributions for regular, offset, and hybrid PDM RZ-DPSK after 5,200 km (~1 million BER samples). Hybrid: 23Gb/s, offset and regular 21.3Gb/s

5. Conclusions

We demonstrated 40 Gb/s transmission over 5,200 km with 60% spectral efficiency and 150 km repeater spacing using a hybrid PDM RZ-DPSK modulation format. The long term Q-factor distribution showed the effectiveness of the hybrid PDM technique (without automatic polarization tracking receiver) in the presence of time varying polarization effects. Better PMD tolerance was also observed for hybrid PDM compared to offset PDM.

6. References

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