Practical 4-Stage Optical PMD Compensator for Mitigating First- and Second-Order PMD Impairments on 40-Gbit/s RZ-D(Q)PSK Signals

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Abstract: A first practical 4-stage optical PMD compensator with ~1-ms response time is experimentally demonstrated for mitigating first- and second-order PMD impairments on 40-Gbit/s RZ-DQPSK signals. BER and DOP degradations are significantly improved by this compensator and a power penalty of <0.5 dB is achieved at $10^{-9}$ BER in the presence of 25-ps DGD and 400-ps² SOPMD.

1. Introduction
As the data rate of optical channels increases to 40-Gbit/s and beyond, polarization mode dispersion (PMD) is considered to be a key limitation for deploying high-speed transmission systems. First-order PMD (i.e., differential group delay (DGD)) generally causes walk-off in time between the two orthogonal polarization states of the signal, resulting in spreading the pulse-width of the signal and thus increasing power penalty and service outage probability. Second-order PMD (SOPMD) results from the depolarization and frequency-dependent dispersion of a PMD vector and it has a statistical correlation to the increasing first-order PMD [1]. The PMD effects on the systems are inherently stochastic and change rapidly with time, making them difficult to mitigate.

Several prior approaches have been reported to combat the PMD effects for 40-Gbit/s deployment. The first is to select fiber routes with low PMD coefficients [2]. However, the PMD of a fiber route changes with time and environmental conditions and the interconnected routes may always have bad fiber sections with high PMD. The second approach is to utilize spectrally efficient modulation formats, such as differential quadrature phase-shift keying DQPSK. The PMD tolerance on the signal is greatly reduced, though never eliminated. Other electronic approaches include electronic dispersion compensator [3], forward error correction [4] and direct detection based digital equalizer [5]. The resulting PMD mitigation may be limited since directly detected signal lacks of phase/polarization information of the corresponding optical signal. Digital signal processing (DSP) is effective in mitigating PMD effect in a polarization multiplexed coherent detection system [6]; however, it may not be used in currently deployed 40-Gbit/s systems using single polarization D(Q)PSK schemes. Consequently, optical PMD compensation remains as an attractive option to effectively compensate for the total PMD [7-9]. It has been shown that multi-stage distributed PMD compensators are most effective in mitigating both the first- and higher- order PMD [10]; however, because of the complexity, single stage and one-and-half stage compensators are mostly developed [8]. PMD compensators (PMDC) of up to 3-stage were reported with limited results [10]. A laudable goal would be to develop efficient algorithm and hardware for adjusting all control parameters of a highly complex multi-stage compensator, and hence greatly reduce response time and improve compensator performance.

In this paper, we experimentally demonstrate a first practical 4-stage optical PMD compensator for mitigating both the first- and second-order PMD impairments on 40-Gbit/s RZ-D(Q)PSK signals. We show that the compensator can maintain the DOP of a 40-Gbit/s RZ-DQPSK signal above 98% with 25-ps DGD present and

Fig. 1. (a) Block diagram of a multi-stage DGD/SOPMD compensator (N=4), consisting of paired polarization controllers (PC) and DGD elements. (b) 1-ms recovery time of PMDC in the presence of the DGD jump from 0 to 21.42ps DGD. 2.5 V corresponds to a DOP of 100%.
94% with 25-ps DGD and 407.7-ps² SOPMD present, when the signal is continuously scrambled at a rate up to 500Hz before the signal going through the corresponding PMD emulator. We further show that the compensator can effectively reduce DGD/SOPMD induced power penalty of both 40-Gbit/s DQPSK and DPSK signals to less than 0.5 dB (at BER of 10⁻⁹). Finally, with a response time of 1 ms, this modulation format-independent optical PMDC is capable of combating PMD impairments under fast PMD and polarization variations.

2. Concept and Device Response Time

The concept of our multi-stage optical PMD compensation technique is illustrated in Fig. 1(a). The compensator consists of 4 pairs of PCs and DGD elements, and is designed to compensate for an average PMD up to 20 ps (60 ps instantaneous DGD). The output signal is monitored by a high speed DOP meter placed at the end of this PMDC. The measured DOP, an indicator of PMD distortion on the signal, is continuously updated to the DSP control circuit to control each PC with an efficient reset-free algorithm to dynamically adjust the polarization alignment on each DGD element. All PCs are continuously adjusted to maximize signal’s DOP. Consequently, signal distortions induced by DGD and SOPMD can be rapidly and effectively mitigated.

Fig. 1(b) shows the measured recovery time of this PMDC in the presence of a DGD jump from 0 to 21.42 ps generated by a fast DGD/SOPMD source (General Photonics PMD-1000). The upper curve shows a corresponding DOP drop from 100% to less than 25% when the PMDC is disabled. In contrast, DOP quickly recovers to the original maximum value in about 1 ms when the PMDC is enabled. Although not shown here, the recovery time caused by an abrupt SOP change is also about 1 ms. Such fast response time is sufficient to mitigate the fast changes of PMD effects caused by vibration or other fast disturbances in the fiber link.

3. System Experimental Results and Discussion

The system experimental setup is shown in Fig 2(a). The 40-Gbit/s RZ-D(Q)PSK signals are generated by a continuous-wave laser (1550.11 nm), externally modulated by a >40-GHz nested Mach-Zehnder modulator (MZM) and a RZ pulse carver, respectively. The signal is then boosted by an erbium-doped fiber amplifier (EDFA) and filtered by a 1.2-nm bandpass filter (BPF). A polarization controller (PC) is placed in front of a polarization scrambler (0.05~500 Hz scrambling rate) and a DGD/SOPMD source in order to generate different PMD effects. The signal, degraded by the DGD/SOPMD source, is sent through the 4-stage optical PMDC, with no prior PMD information required. Inside the compensator, about 1% of the output signal is tapped and sent to a DOP meter for measuring and monitoring, and 99% of the signal is sent to the bit error rate measurement set, including a variable optical attenuator (VOA), EDFAs, a BPF, a delay-line interferometer (DLI), and balanced receivers (BRx). Fig. 2(b) illustrates the captured eye diagrams of 40-Gbit/s RZ-D(Q)PSK signals without and with PMDC under different (DGD,SOPMD) combinations, respectively. The distorted signals are effectively improved by this PMDC.

A polarization scrambler with scrambling rates of 0.05–500 Hz is used to investigate the rapid compensation performance of this PMDC. Fig. 3(a) shows the long-term measurements of DOP, without and with PMDC, of a 40-Gbit/s RZ-DQPSK signal under 500 Hz scrambling and passing through a 25-ps DGD. Without PMD compensation, the signal’s DOP fluctuates wildly between 15% and 100% under such high scrambling rate. On the other hand, the signal’s DOP is stabilized with PMD compensation enabled. The average DOP values at a scrambling rate of 1–500 Hz are >98%. For another case with 25-ps DGD & 407.7-ps² SOPMD, the average DOP values at a scrambling rate of 1–500 Hz are >94%. Fig. 3(b) shows the measured DOP of 40-Gbit/s RZ-D(Q)PSK signals in the presence of different DGD values. As expected, the DOP value decreases with DGD increase. The DGD tolerance is different for 40-Gbit/s RZ-DQPSK and RZ-DPSK signals due to different spectral bandwidths. With PMDC, the DOP degradations are effectively compensated. Fig. 3(c) further shows the BER improvement in the presence of different DGD for 40-Gbit/s RZ-DQPSK and RZ-DPSK, respectively.
Fig. 4(a) illustrates the measured DOP variations of a 40-Gbit/s RZ-DQPSK signal in the presence of different DGD and SOPMD. The polarization scrambler is disabled in this case. Without PMDC, the measured DOP ranges from 100 to 3.3% in the presence of 0~40-ps DGD and 0~1200-ps² SOPMD. In contrast, the degraded DOP caused by various DGD and SOPMD is compensated and increases to >90% when the PMDC is enabled, showing the effective DOP improvement. Moreover, Fig. 5 shows the BER measurements of 40-Gbit/s RZ-DQPSK and RZ-DPSK signals in the presence of different DGD and SOPMD, respectively. For a 40-Gbit/s RZ-DQPSK signal, (20-ps DGD,400-ps² SOPMD) and (25-ps DGD,400-ps² SOPMD) cause >1-dB and >3-dB power penalty at a BER of 10⁻⁹, respectively. With the PMDC, the measured power penalties of both cases are less than 0.5 dB. For a 40-Gbit/s RZ-DPSK signal, the tolerance becomes smaller as compared to 40-Gbit/s RZ-DQPSK. (10-ps DGD,200-ps² SOPMD) and (15-ps DGD,200-ps² SOPMD) induce >1.5-dB and >4-dB power penalty at a BER of 10⁻⁹, respectively. Similarly, the measured power penalties for both cases are less than 0.5 dB with the PMDC.

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Reference