Why Coherent Detection Systems May Fail at Compensating for Polarization Mode Dispersion

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INTRODUCTION

Given that 40G/100G coherent detection systems are now extensively deployed, the telecommunications industry has a solid grasp of their performance. Along with many other features, coherent systems are reputed to compensate for polarization mode dispersion (PMD) in real time thanks to advanced algorithms that have made it possible to compensate for such impairments in the electrical domain, and advanced modulation formats that have made it possible to encode more bits per symbol (keeping the same baud rate). However, do the systems actually deliver on this promise?

In this paper, EXFO (a leader in field testing), and General Photonics (an expert in lab measurements) have joined forces to examine the reasons why PMD compensation might fail or be ineffective. This paper will cover the basic technical concepts relevant to this discussion (PMD, DGD, etc.), and present the main factors that could affect the performance of PMD compensation. The paper will also discuss PMD-related tests performed in the laboratory to optimize and/or stress PMD compensation algorithms and circuitry, as well as the PMD tests carried out in the field to identify PMD issues in advance and reduce their frequency. The paper will conclude with a short overview of the PMD-related testers available from EXFO and General Photonics.

BASICS OF COHERENT DETECTION: PMD AND SOP

Polarization, which is a property of light, is defined in terms of the pattern traced out in the transverse plane by the electric field vector as a function of time. The light is 100% polarized if it has a defined, repeatable trace that represents its state of polarization (SOP). Polarized light can be classified into the following three groups: linearly polarized, circularly polarized and elliptically polarized light. Poincaré sphere representation is used to describe the polarization and changes in polarization of a propagating wave. Any given polarization state corresponds to a unique point on the sphere, as shown in Figure 1, below.

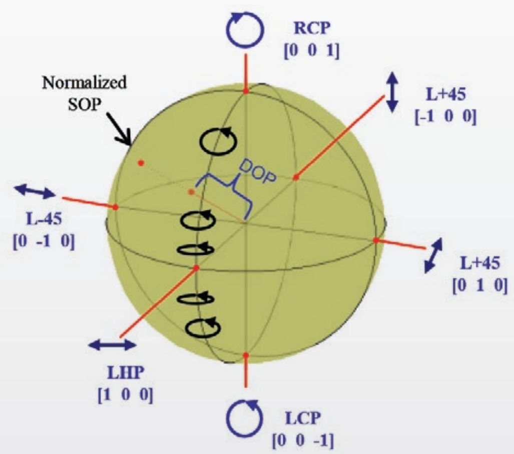

Figure 1. Poincaré Sphere Representation

The fact that optical fibers are inherently anisotropic media, along with other external factors that could alter the birefringence of the fiber, cause the two orthogonal polarization states of an optical pulse to travel at different speeds. The differential group delay (DGD) between the two orthogonal states represents the first-order PMD, as illustrated in Figure 2. Assuming a fixed principal state of polarization (PSP) and a narrow line width, first-order PMD can be assumed to be wavelength-independent and solely dependent on the length of the fiber. In fact, experiments show that the mean DGD of a long fiber increases linearly with the square root of the fiber length. The worst-case first-order PMD occurs when the SOP of the input signal is 45 degrees from the PSP of the fiber, which confirms how dependent PMD is on SOP.

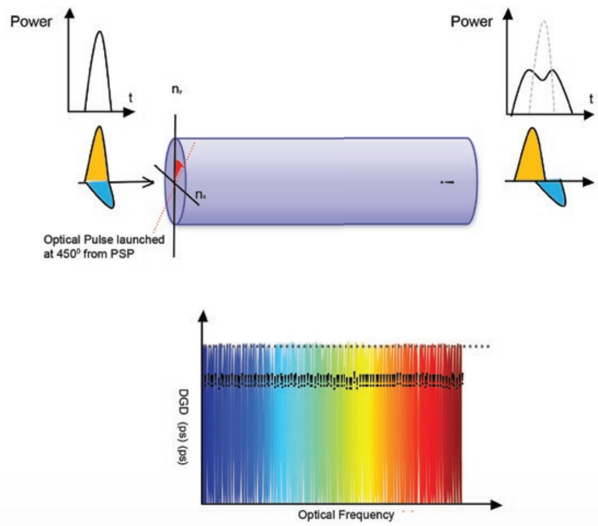

Figure 2. First-Order PMD

However, in a real fiber link, the PSP is not fixed. Instead, the fiber can be considered a concatenation of many randomly oriented retardation plates. In the absence of polarization-dependent loss (PDL) or polarization-dependent gain (PDG) in the fiber link, these retardation plates are optically equivalent to a single retardation plate with an effective DGD and a pair of effective orthogonal PSPs (can be either linear or circular) for a given optical frequency (λ). Because the optical pulse is composed of many wavelengths, the dependency of PSP and DGD on the wavelength could cause further pulse spreading, and is referred to as second-order PMD, as shown in Figure 3.

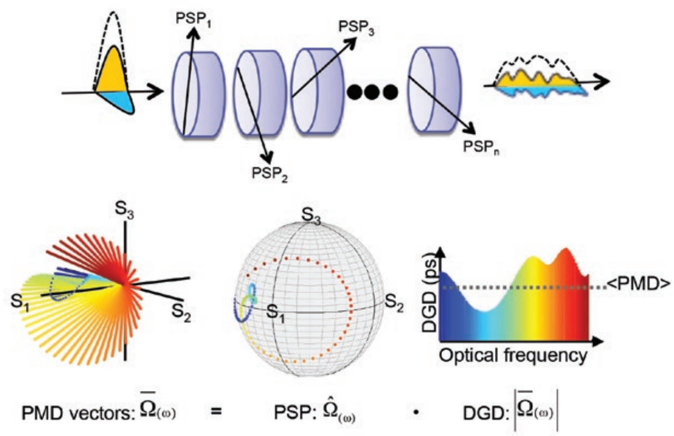

Figure 3. Second-Order PMD

It should be noted that the first term of the PMD vector equation shown in Figure 3, where the direction of the vector depends on wavelength, has the dominant effect. The polarization states of the spectrum of an input signal will disperse around the PSP, thus causing spectral depolarization and effectively decreasing the signal's degree of polarization (DOP). This will affect the PMD compensation at the coherent receiver side, because polarization demultiplexing will no longer be done perfectly.

Older systems (e.g., 10G) are referred to as direct detection systems, because their detectors consist of a simple photodiode that tracks changes in signal amplitude, which is how information is encoded in modulation schemes such as on-off keying, return-to-zero (RZ) and non-return-to-zero (NRZ). Direct detection systems contrast with coherent systems in their level of complexity, as shown in Figure 4 below.

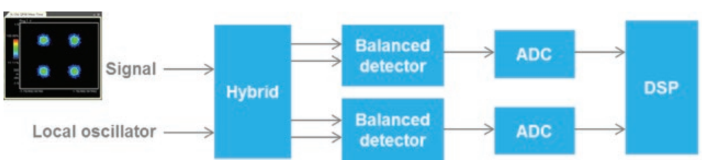

Figure 4. Block Diagram of a Coherent System's Rx

A coherent system features a local oscillator–a laser that is mixed with the incoming signal–and the resulting signal goes through a series of components before arriving at the digital signal processor (DSP), where PMD compensation takes place. Coherent detectors allow for the use of advanced technologies like polarization multiplexing (two signals on orthogonal polarizations at the same wavelength) and complex modulation formats based on phase modulation (QPSK, DQPSK, etc.), or both phase and amplitude modulation (16-QAM). While 40G is available in both coherent and direct detection (non-coherent) formats, 100G and above is almost always coherent.

PMD AS A STOCHASTIC PHENOMENON

As stated earlier, PMD is tightly related to the SOP. Both PMD and SOP changes are caused directly by the fluctuations in the birefringence of the optical fiber. The major causes of the birefringence are the asymmetry of the fiber-optic strand (resulting during manufacturing) and mechanical stresses on the fiber. These factors are relatively static and do not change over time. However, there are other external factors that can change the birefringence, such as temperature, pressure, macrobending/microbending (slow over time), wind-caused vibration, train-induced acoustic vibration, and lightning strikes (fast and sudden) that are random in nature, resulting in changing values of SOP and PMD over time.

Studies have shown that the rate of change of SOP follows the Rayleigh distribution, whereas DGD changes follow the Maxwellian probability distribution, as shown in Figure 5.

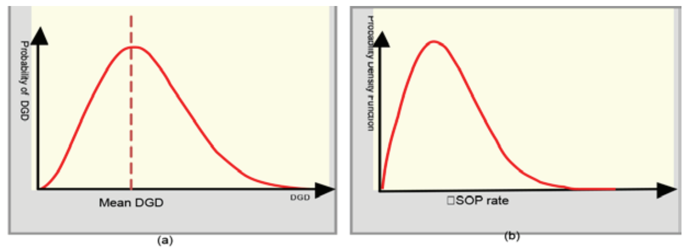

Figure 5. DGD (a) and SOP (b) Probability Distributions

CASE STUDY DISCUSSION

EXFO and General Photonics are aware of several cases in which coherent systems could not properly compensate for PMD. The first case took place in Europe, where a service provider witnessed intermittent bit-error-rate (BER) bursts lasting 20 to 30 seconds on the 100G channels of a single fiber. Those bursts occurred at random moments, without any specific pattern. Due to their random nature, PMD and SOP were prime suspects in the investigation to determine the cause of these failures. After traffic was transferred to another fiber with low PMD, the problem was fixed. The initial fiber, now without traffic, had been tested for PMD and had exhibited a high PMD value.

In Russia, a major service provider operating a 100G long-haul network with many aerial spans of 70 km to 100 km has experienced sudden increases in BER that occur at the same time as fast changes in DGD, as shown by the network management system. A full investigation of this issue has not been completed, but the correlation between BER and DGD indicates that the root cause is likely due to the PMD compensation algorithms having trouble handling sudden events that affect the fiber, such as lightning or wind.

In Japan, a customer deploying a 100G DP-QPSK system observed issues with fast changes in the polarization state. The phenomenon happens at >50 kHz SOP changing (which is considered high), and has been shown to happen during weekdays, but not on weekends.

FACTORS THAT CAN LEAD TO PMDC FAILURES

Coherent detection systems perform four main polarization-related functions: 1) continuous SOP tracking, 2) polarization demultiplexing, 3) PMD compensation (PMDC), and 4) PDL mitigation (PDLM). These functions are accomplished using high-speed DSP circuits and algorithms in the transceivers. Any external factors that can affect the performance of the first two functions will lead to degradation in the performance of PMD compensation. Below is a list of seven potential factors:

- Fast SOP changes
- Abrupt SOP change
- Loss of SOP orthogonality
- Fast PMD changes
- Sudden PMD change
- Large PMD values
- The presence of PDL

The SOP of an optical pulse randomly changes as the signal propagates inside a fiber. The rate of change of SOP can vary from very low to extremely fast. Every coherent receiver has an SOP tracking speed specification, which defines the highest rate of change of SOP (measured in radians per second) at which a system can operate properly without tracking loss. If the SOP changes faster than that limit, or suddenly jumps, the transceiver will be faced with the challenge of keeping up with the fast changes in SOP while perfectly demultiplexing the Pol-Mux signal. In addition, the two polarization channels of the Pol-Mux signals would ideally be perfectly orthogonal during transmission. However, imperfection in the polarization combiner at the transmitter and/or the presence of PMD, PDL and non-linearity in the system may degrade the orthogonality of the two polarization channels and cause crosstalk. When the signal arrives at the receive end, imperfection in the orthogonality will degrade the polarization demultiplexing function, which will ultimately affect the PMD compensation.

Moreover, the fact that PMD-induced penalty is random in nature makes the electronic PMD compensation method challenging. If the instantaneous PMD changes quickly or jumps abruptly, the PMDC algorithm and circuit might be inefficient in compensating for PMD. Also, as the fiber ages, the intrinsic PMD of the fiber can change due to environmental factors. Adding in sudden external factors capable of changing the PMD, the overall PMD could pass the threshold PMD range at which the transceiver is capable of compensation. More importantly, the presence of PDL in a long fiber link leads to a complex interaction with highly erratic and unpredictable results, causing the optical pulses to broaden much more than the value expected from the PMD alone.

PMD COMPENSATION-RELATED TESTS IN THE LAB

1) SOP Tracking Speed

SOP tracking speed is defined as the highest polarization variation rate at which the system can still operate properly without tracking loss. Test/R&D engineers can use this test to see how well the polarization tracking/demultiplexing circuitry and algorithm are able to track polarization variations of different patterns at different speeds. The recommended SOP pattern (Tornado) for such tests is shown in Figure 6. The SOP should cover the Poincaré sphere, and the probability distribution function (PDF) should be centered at the high SOP rate of changes. Having a narrow band at high SOP enhances the testing repeatability and is optimal for comparing the performance of two different coherent detection systems. This test is an indication of a transceiver's "agility."

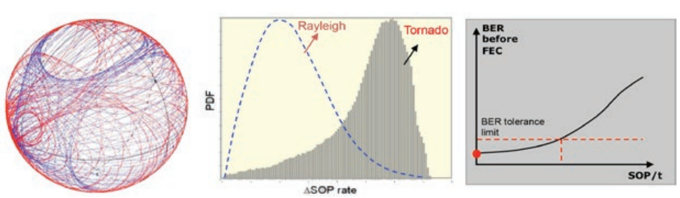

Figure 6. Torando Mode for SOP Tracking Speed Test

2) SOP Recovery Time

SOP recovery time is the time required for an SOP tracking circuitry and algorithm to recover from a loss of track caused by an abrupt polarization jump. This test shows how well the demultiplexing circuitry and algorithm respond to sudden SOP jumps, as shown in Figure 7.

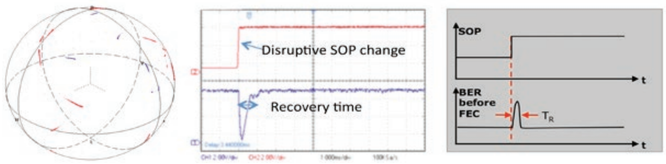

Figure 7. Step Index SOP Change for Recovery Time Test

3) SOP Orthogonality

Polarization orthogonality reflects the polarization-channel crosstalk. Practically, it should be measured after two polarization channels are combined at the transmitter end, and before they are separated at the receiving end. In an ideal system, the angle between polarization components is 90 degrees. This test is an indication of the impairments in your system that are responsible for losing orthogonality.

4) PMD Tracking Speed

PMD tracking speed is defined as the highest PMD variation speed at which the PMD compensator is still effective in reducing PMD-induced signal distortion. Specified in picoseconds per second, it defines how fast a PMDC can respond to PMD value changes. To carry out such a test, a deterministic and repeatable first- and second-order PMD generator is required. In addition, the PMD emulator must be controllable in order to vary PMD over a wide range of PMD values with different speeds and transit times, as shown in Figure 8.

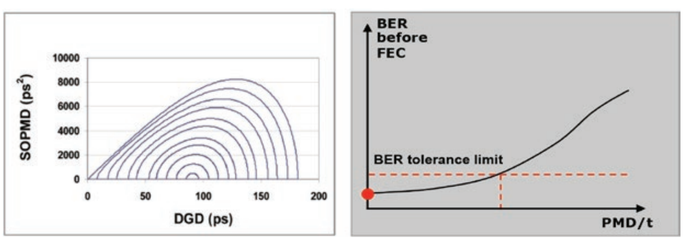

Figure 8. Different PMD Traces for PMD Tracking Speed Test

5) PMD Recovery Time

PMD recovery time is defined as the time required for a PMDC to recover from a loss of track caused by an abrupt PMD value jump. This test measures how well a PMDC responds to sudden changes in PMD. A fast PMD generator with a wide PMD range is highly desirable for carrying out this test, as shown in Figure 9.

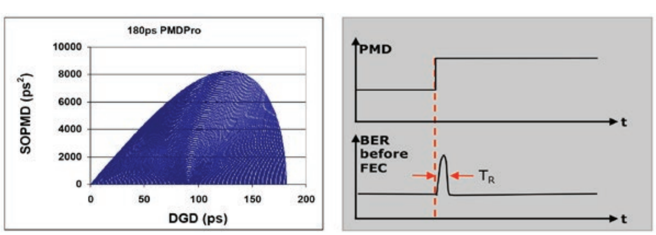

Figure 9. Step Index PMD Change for PMD Recovery Time Test

6) PMD Tolerance Range

PMD tolerance range is defined as the maximum PMD value in a transmission system at which data can be transmitted with a BER smaller than that required by the system design. It indicates how well the PMDC works on mitigating PMD effects to extend the system's PMD tolerance.

7) SOP, PMD, and PDL Combined Test

This combined test stresses the system by emulating the three random phenomena simultaneously. The fast changes in SOP will cause the PMD effect on the signal to be random. In addition, the presence of PDL will cause the pulse to be speared in time, leading to more signal distortion. A recommended test setup is shown in Figure 10.

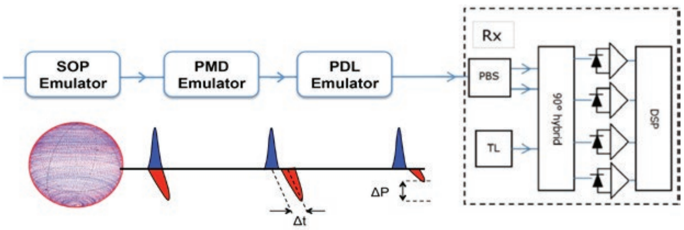

Figure 10. All Polarization-Impairment Test Setup

PMD COMPENSATION-RELATED TESTS IN THE FIELD

8) Long-Term PMD Monitoring of the In-Service Link

It is often desirable to be able to measure the PMD of a transmission link without interrupting signal transmission. The average PMD of the fiber link can be obtained by averaging the instantaneous PMD of multiple DWDM channels measured at about the same time using the PMD compensation method (see the following link for full details: http://www.generalphotonics.com/downloads/techpubs/In-service-light-path-PMD-monitoring-by-PMD-compensation.pdf). The insert in Figure 11 shows the long-term PMD monitoring result for a single channel.

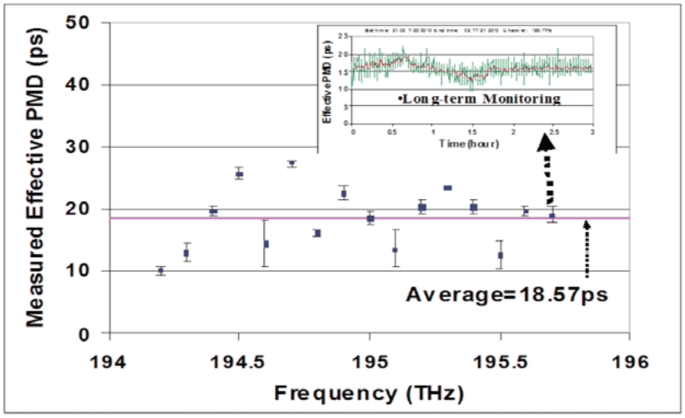

Figure 11. Average PMD of a Link with Live Traffic

9) Long-Term SOP Monitoring of the In-Service Link

Due to the random nature of SOP, it is often necessary to understand how it changes in a real fiber, and/or to try to record sudden SOP changes in order to understand how fast an SOP can change on a specific link and when. This necessitates a fast polarimeter instrument with logging capabilities that can stream the four Stokes parameters.

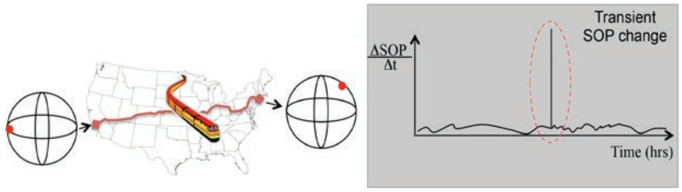

Figure 12. Long-Term SOP Logging for Detection of Instantaneous Changes in SOP

10) PMD Test as Part of Fiber Characterization (before Commissioning)

The PMD test carried out during fiber characterization is the most common PMD test in the field. Recommended in the ITU G.650.3 standard, the PMD test makes it possible to avoid all the risks described in the previous section. The best moment to carry out a PMD test in the field is prior to commissioning, because most PMD testers only work on fiber without traffic.

11) Distributed PMD as Part of Fiber Characterization (before Commissioning)

If a PMD test reveals a high PMD value during fiber characterization, it is possible to isolate the defective segment(s) with a distributed PMD test, which is similar to an OTDR test, but for PMD. As shown in Figure 13, the distributed PMD test displays the PMD value as a function of distance (the curve in red). With close to a decade of performing distributed PMD analysis around the world, EXFO has observed that in most cases of high PMD, only a small segment under 5 km generates more than 70% of the total span of PMD.

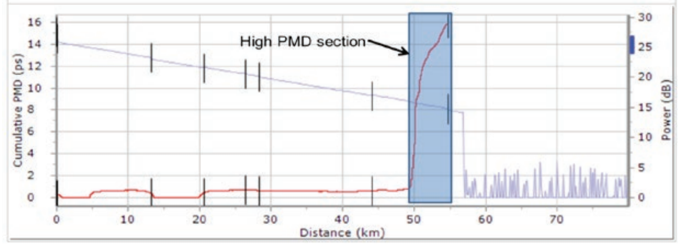

Figure 13: Distributed PMD Test

12) PMD Test on Live Fiber

Once the traffic is live, it is also possible to qualitatively assess the PMD non-intrusively using the WDM Investigator software option available on EXFO's OSA. The OSA can be connected to monitor ports or taps to analyze PMD on a per-channel basis (non-coherent channels only) without any traffic interruption. Figure 14 shows the user interface, where green indicates "pass," yellow means "warning," and red represents "danger."

Figure 14: WDM Investigator User Interface

HOW TO REDUCE THE RISK OF PMDC FAILURES IN THE FIELD

As previously shown, coherent systems may fail to compensate for PMD due to any of the following seven main reasons: sudden PMD jumps, fast PMD changes, PMD exceeding the PMD threshold for the system, fast SOP changes, abrupt SOP jumps, the presence of PDL, and loss of orthogonality. Therefore, it intuitively makes sense that a fiber with lower PMD is less likely to exceed the system's PMD threshold, but how can the other six risks be reduced? In short, PMDC failures can be reduced by measuring the PMD of each fiber and by not using the fibers with high PMD, because all seven risk factors for PMD compensation failure **increase** when the fiber PMD is high. To better understand why, we will separately examine the PMD-related failures and the SOP-related failures.

First, consider the two reasons for PMD-related failure, i.e., sudden PMD jumps and fast PMD changes. When the fiber PMD is small for a coherent system (e.g., 1 ps or 2 ps), changes in temperature and mechanical stresses do not induce large DGD changes. When the fiber PMD is high (e.g., 6 ps or 7 ps), small changes in temperature and mechanical stresses induce large DGD changes. This is because the orientation of the PSPs (fast and slow axis) rotates considerably with small movements and/or small temperature changes when PMD is high. In addition, high PMD means that DGD varies a lot as a function of wavelength. Therefore, PMD jumps and fast PMD/DGD changes are more likely to occur with high-PMD fiber.

The next step is to examine the two SOP-related failures: fast SOP changes and abrupt SOP jumps. When the fiber PMD is small, changes in temperature and mechanical stresses do not induce large SOP changes. When the PMD of the fiber is high, small changes in temperature and mechanical stresses significantly rotate the PSPs (fast and slow axis).

This means that the SOP will undergo fast changes with minimal temperature changes and/or small mechanical stresses when PMD is high. To picture this, think of a DGD graph: temperature changes are somehow comparable to a DGD shift in frequency, where both the amplitude and the number of transitions are proportional to PMD. Therefore, SOP jumps and fast SOP changes are more likely to occur with high-PMD fiber.

PMD-RELATED TESTERS

General Photonics provides a complete line of emulation products for network and system characterization, and for 100 Gbit/s and 400 Gbit/s coherent detection systems in particular. These include the PMD-1000 PMD source, which can generate individual, deterministic PMD values (first- and second-order PMD), and different PMD variations or statistical distributions; the PDLE-101 PDL source, which can generate individual PDL values or PDL variation patterns; the MPC-202 polarization controller, which emulates many kinds of polarization variations; and the ODG-101 digital optical delay generator, which emulates chromatic dispersion and signal delays. In addition, the POD-201 in-line polarimeter can be used for instantaneous and long-term monitoring of polarization variations in a system. Figure 15 shows some of the main measurement instruments for stressing coherent detection systems.

Figure 15. POD-201, PMD-1000, PDLE-101 and MPC-202 from General Photonics

EXFO offers a wide range of rugged, portable PMD field testers, including the FTB-5700, the world's only single-ended dispersion tester, which can measure chromatic dispersion and PMD from a single location, whereas other testers on the market require two technicians, each located at either end of the link. EXFO also offers the FTB-5600, the world's first and only distributed PMD analyzer, as well as the FTB-5500B PMD Analyzer designed to measure the PMD of amplified links, as shown in Figure 16.

Figure 16. FTB-5700 and FTB-5600 from EXFO

CONCLUSION

This paper has demonstrated that although coherent detectors promise to compensate for PMD, they can fail for the following reasons:

- Fast SOP/PMD changes
- SOP/PMD jump
- PMD value > PMDC limit

All these failures have negative consequences, because they lead to increased BER. Several coherent transceiver tests in the lab can help assess the effectiveness of PMD compensation algorithms. In the field, it is paramount to avoid using fibers with high PMD in order to reduce outage probability due to PMD compensation problems. This can be achieved by systematically measuring the PMD of fibers during commissioning.

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