Polarization Optimized PMD Source Applications

PMD mitigation in 40Gb/s systems

As the bit rate of fiber optic communication systems increases from 10 Gbps to 40Gbps, 100 Gbps, and beyond, polarization mode dispersion (PMD) has more and more impact on system performance. PMD generally causes the two principal polarization components of a light signal to travel at different speeds and hence spreads the bit-width of the signal, as shown in Figure 1A. Consequently, it causes an increase in bit-error rate (BER) and service outage probability. Unlike other system impairments, such as chromatic dispersion (CD), the PMD effect on the system is random in nature and changes rapidly with time, making it difficult to mitigate.

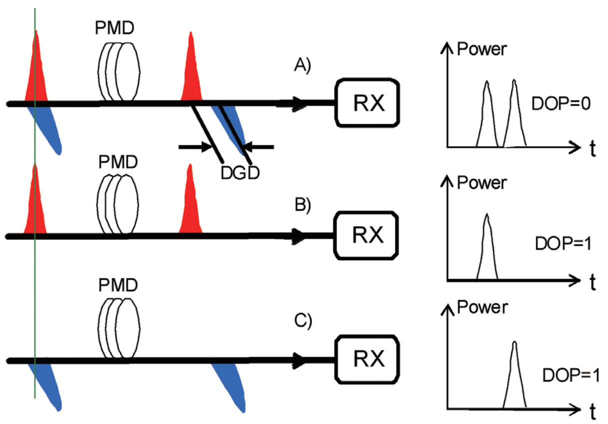

Figure 1 Illustrations of the PMD effect on an optical signal. A) The SOP of the input signal is aligned 45 degrees from the PSP of the fiber link, causing the worst-case signal distortion. In this case, if the DGD is larger than the width of one bit, then the DOP=0 because the two orthogonal polarization components have the same power, with no phase relationship. B) and C) The SOP of the input signal is aligned with the slow or fast PSP axis, respectively. In these cases, no signal distortion occurs except the slight late or early arrival, respectively, of the pulse. The DOP of the signal remains at 1. In all 3 cases, the PMD of the link remains the same, but the effect on the signal is different due to the different input polarization states.

Several methods with varying success rates exist to mitigate PMD effects for 40G deployment. The first is to select fiber routes with low PMD coefficients. Such a method requires extensive survey of all available fiber routes to identify and cherry-pick those with sufficiently low PMD. However, such an approach has three potential drawbacks: First, the PMD of a fiber route changes with time as the environmental conditions around the fiber change, including land movements caused by earthquake, flood, or mud-slides. A route that is good today may become bad in the future. Second, interconnected fiber routes may always have bad fiber sections with high PMD, rendering the selection of low PMD fiber routes throughout the system impractical. Finally, the supply of fiber routes with low PMD values will eventually be exhausted as 40G deployments increase.

The second method is to use bandwidth efficient modulation formats, such as DPSK or DQPSK. Such modulation formats reduce the effective bandwidth of a 40Gb/s channel to that of a 20Gb/s or even a 10Gb/s channel. Consequently, the impact of PMD on the signal is greatly reduced, though never eliminated.

The third approach is electronic PMD compensation, in which forward error correction (FEC) or other algorithms are used to reduce the PMD effect on the signal after the optical signal is converted into an electrical signal. However, because the electrical signal does not contain the phase information of the corresponding optical signal, the resulting PMD effect reduction is limited.

Optical PMD compensation is another attractive approach. An optical PMD compensator generally contains one or more polarization controllers, a PMD generation device, a PMD monitoring device, and a microprocessor based circuit, as shown in Figure 2. The circuit receives an error signal from the PMD monitoring device and instructs the PMD generation device to adjust the PMD values and the polarization controller to adjust the polarization state input to the PMD generation device to minimize the error signal from the PMD monitoring device. The PMD is compensated when the PMD generated by the PMD generating device is the same in value as that of the fiber link, but with its slow axis aligned with the fast axis of the fiber link.

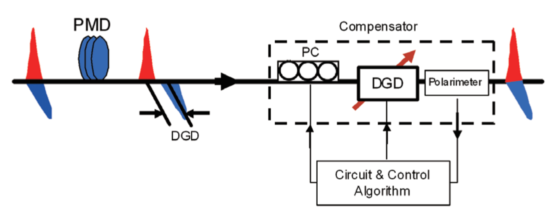

Figure 2 Optical PMD compensation. The DOP measured by the polarimeter is used as PMD effect indicator.

The final approach is polarization multiplexed coherent detection. Because the detected electrical signals in this approach contain all of the amplitude, phase, and polarization information of the corresponding optical signal, any optical signal impairments, including PMD, can be compensated by digital signal processing. In addition, because of the quadrupled spectrum efficiency resulting from QPSK modulation and polarization multiplexing, the effective optical signal bandwidth of a 40G channel is about the same as that of a 10G TDM channel. Consequently, the PMD effect on such a narrow band signal is also greatly reduced even without PMD compensation. Although transceivers incorporating polarization multiplexed coherent detection may still not be cost-effective compared with other approaches for 40Gb/s transmission, they are most attractive for 100Gb/s and higher speed transmissions.

Instruments required for PMD related tests

PMD source for PMD tolerance test

No matter which approach is taken, it is desirable to have an instrument capable of testing the performance of different methods in mitigating PMD effects. This test is called a PMD tolerance test. The general setup is shown in Figure 3A. The key instrument in this setup is the PMD source, which can generate precise 1st and higher order PMD values. The bit-error rate (BER) of the system, or another such performance indicator, is measured as the 1st order PMD (DGD) values generated by the PMD source are gradually increased until the BER reaches the limit set for the system, as shown in Figure 3B. The corresponding DGD is the 1st order PMD tolerance of the system. Both the 1st and 2nd order PMD (SOPMD) values can also be increased as the BER of the system is measured and plotted, as shown in Figure 3C. The system outage probability can be calculated from the data obtained.

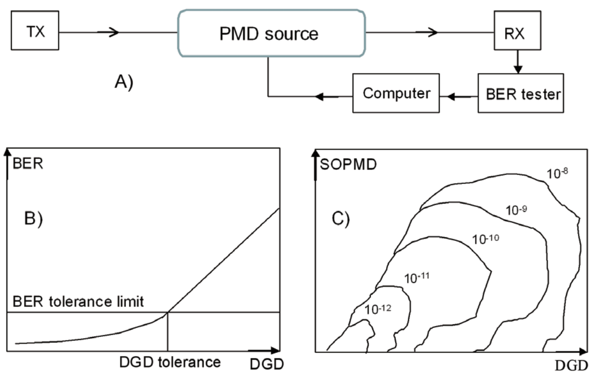

Figure 3 A) PMD tolerance test setup using a PMD source. The computer selects PMD settings and collects BER readings. B) BER vs. DGD curve. The DGD tolerance of the system for a given BER threshold can be deduced using the curve. C) Map of BER vs. DGD and SOPMD. Each contour represents a BER value. The PMD tolerance can be obtained from the contour plot.

PMD tolerance test results can be used by network operators to compare systems made by different vendors and to verify the PMD related specifications promised by the vendors. They can also be used by system vendors to 1) determine which PMD mitigation approach is most suitable to adopt, 2) to fine tune the PMD mitigation related parameters in the transceivers during system development, and 3) to perform output quality control of the final system, including transceivers, for the PMD related specifications.

Importance of polarization optimization: The PMD effect on a system is highly polarization dependent. When the input state of polarization (SOP) is aligned or counter-aligned with the principal state of polarization (PSP) of the fiber link or the PMD source, the PMD has no effect on the signal, and therefore no effect on system performance, as shown in Figure 1. By contrast, when the input SOP is aligned 45 degrees from the PSP of the fiber link or PMD source, the PMD has its maximum effect on the transmitted optical signal, and hence its worst-case effect on system performance. The effect of PMD on data can be characterized by the degree of polarization (DOP) of the optical signal, because PMD causes depolarization of the optical signal, as shown in Figure 1. The smaller the DOP, the larger the PMD effect. In general, the DOP of the signal passing through a medium with nonzero 1st order PMD can be expressed as:

$$DOP(\tau) = \sqrt{4(\gamma^2 - \gamma)[1 - R^2(\tau)/R^2(0)] + 1} \qquad (1)$$

where τ is the DGD value of the medium, γ is the power distribution ratio of the two polarization components with respect to the principal state of polarization (PSP) of the DGD element (γ = ½ when the powers of the two polarization components are equal or when the input SOP to the medium is oriented 45 degrees from its PSP) and $R(\tau)$ is the self correlation function of the optical signal, which decreases as τ increases. Clearly, the DOP reaches a minimum value of $R(\tau)/R(0)$ when γ = ½ or when the input SOP is 45 degrees from the PSP of the DGD medium. At this SOP, the PMD has its worst effect on the quality of the signal. Conversely, when γ = 1 or when the input SOP is aligned with the PSP, the DOP always remains at its maximum value of 1, regardless of the DGD value.

When higher order PMD is present, the PSP is different for different wavelength components of the signal and Eq. (1) may no longer hold. Nevertheless, there always exists an input SOP for which the DOP of the signal at the output end is at a minimum and therefore, for which the PMD has the most severe impact on the quality of the signal. There also exists an input SOP at which the PMD has the least effect on the quality of the signal.

Coherent detection systems: Most coherent detection systems use polarization multiplexed signals. Since both polarization components are present, the DOP of the signal is not a reliable indicator of the severity of the PMD effect. Therefore, to ensure that the worst-case PMD effect is achieved, polarization scrambling must be used before the PMD generator.

PMD source for PMD compensator evaluation

A PMD source is also necessary to evaluate the performance of a PMD compensator, whether optical or electrical, as shown in Figure 4. First, one can evaluate the system improvement margin at different PMD settings. Second, by gradually increasing the PMD values while measuring the BER of the fiber link, one can evaluate the PMD compensation range of the compensator. 3) Third, by changing the PMD value rapidly, one can determine the speed of the compensator response to quick PMD variations in the link. Finally, by changing the SOP rapidly at different PMD settings, one can determine the response time of the compensator to the change in SOP at each PMD setting. Therefore, a PMD source with fast PMD change and fast polarization control capabilities is attractive for PMD compensator evaluation.

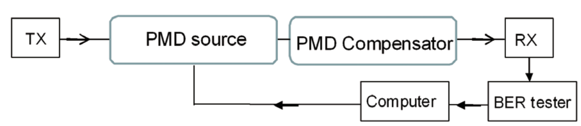

Figure 4 PMD source for PMD compensator evaluation. For electrical compensation, the compensator may be inside the receiver (RX). The plots shown in Figure 3 can be generated here with PMD compensation at different PMD settings of the PMD source.

PMD analyzer or monitor for link PMD determination

The PMD values of fiber routes generally must be measured before link deployment. This requires PMD analyzers. In general, a PMD analyzer requires a large-bandwidth light source, whether it is tunable laser-based or broadband source-based. As mentioned previously, the PMD of fiber routes may change with time, due to changes in environmental conditions. For a ROADM network, after the fibers are lit, the wavelength channel for each transceiver pair is determined and is confined within a 50GHz bandwidth. Therefore, PMD analyzers requiring broadband light sources cannot be used to characterize such a system. In addition, it is undesirable to disconnect the transceivers and insert a PMD analyzer in the link, because this would cause a severe service interruption. It is therefore attractive to be able to determine the PMD value of a live link while both the transmitter and receiver are operational. This capability is important for the diagnosis of fiber routes with performance issues.

Drawbacks of PMD sources currently on the market

Currently available PMD sources, such as those from NewRidge, are rather rudimentary. They are capable of generating both 1st and 2nd order PMD, but the input SOP to the PMD source is not controlled and therefore changes with external disturbances on the input fiber. Consequently, the effect of the PMD on the signal is unpredictable and changes randomly, because the PMD effect on the signal is strongly dependent on the input SOP, as shown in Figure 1. In order to obtain predictable test results, it may be necessary to scramble the input SOP to obtain a PMD effect on the signal that is averaged over a large numbers of input SOPs. However, such a process not only significantly slows down each test point, but also adds the cost of a polarization scrambler to the test setup.

Other drawbacks of present PMD sources include a slow PMD change speed and low PMD value repeatability. One PMD source on the market uses multiple birefringent crystals aligned linearly. Each crystal can be rotated by an electrical motor. Different PMD values are generated by rotating different crystals at different angles. Consequently, the speed and repeatability of PMD generation are limited by the speed and angular accuracy of the electrical motors and their associated control circuits.

Desirable features for a PMD source

High repeatability and high speed of generation of 1st and higher order PMD values are desirable in a PMD source because they enable fast, repeatable PMD tolerance tests and PMD compensator evaluation.

Automatic optimization of input SOP is also highly advantageous. As described previously, PMD tolerance tests can be made much simpler if the input SOP to the PMD elements inside a PMD source can be controlled and optimized such that each PMD value has the most severe possible impact on the quality of the optical signal, regardless of polarization changes caused by disturbances to the fiber link. Specifically, the input SOP can be automatically maintained at an alignment of 45 degrees from the PSP of the PMD source, or the output DOP can be automatically maintained at a minimum value by actively controlling the input SOP.

PMD compensation is also an extremely attractive function. First, system vendors and network operators need to know how much system performance can be improved by adding PMD compensation in order to decide whether to deploy PMD compensators on a link with performance issues. Second, if PMD compensation significantly improves the system performance, it can be determined that PMD is the major cause of performance degradation; otherwise, other impairments should be considered. Therefore, a PMD source with PMD compensation capability can be used for the diagnosis of system problems. Finally, optimized PMD compensation can help to determine the PMD values of the fiber link, because the PMD value used for optimal PMD compensation is close to the real PMD value of the fiber link. Such a feature is attractive for frequent PMD monitoring of a live fiber link, a task that cannot be accomplished with PMD analyzers currently on the market.

The polarization optimized PMD source

General Photonics' polarization optimized PMD source meets all of the requirements described above. This advanced PMD source is constructed with a polarization controller (PC), a polarimeter at the input end, a PMD generator, a second polarimeter at the output end, and a digital signal processor (DSP) based electronic circuit, as shown in Figure 5. The two polarimeters are used to provide feedback signals to the DSP circuit for full polarization optimization. The circuit receives the polarization measurements from the two polarimeters, processes them, then sends commands to control the PMD generator and the polarization controller. The circuit can use the SOP information from the input polarimeter as the feedback to control the PC and generate any SOP the user prefers. In particular, it can automatically align the SOP to 45 degrees from the PSP of the PMD generator. This polarization state causes the PMD generator to have the worst-case 1st order PMD (DGD) effect on the optical signal at any DGD setting, and is therefore the preferred SOP for DGD tolerance tests for transceivers and fiber systems. Alternatively, the circuit can use the DOP information from the output polarimeter as the feedback to control the PC. The input SOP that minimizes the output DOP causes the PMD generator to have the worst-case total PMD effect on the optical signal, and is therefore the optimal polarization state for total PMD tolerance tests of transceivers and fiber systems. Finally, the optimized input SOP obtained by maximizing the DOP from the second polarimeter enables PMD compensation.

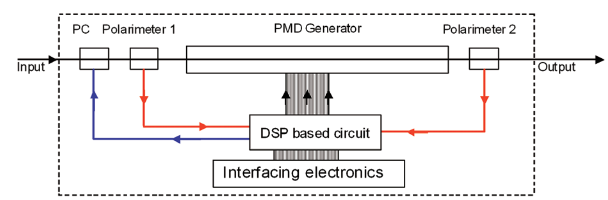

Figure 5 System diagram of polarization optimized PMD source. The DSP based circuit is used to 1) process information from the polarimeters and control instructions from users, 2) instruct the PMD generator to select desired PMD values, 3) control the PC to optimize the input SOP for various functions.

The PMD generator used in the PMD source is based on General Photonics' patent pending ternary polarization rotation technology. The generator is constructed using a series of birefrigent crystals, with a ternary polarization rotator sandwiched between each pair of adjacent crystal segments, as shown in Figure 6. The crystals are arranged in descending order, with lengths decreasing sequentially by a factor of 2. Each rotator is capable of rotating the state of polarization (SOP) by +45, 0, or -45 degrees.

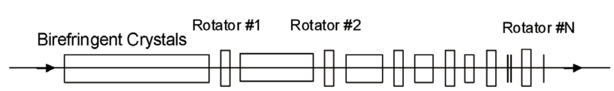

Figure 6 The construction of a PMD generator made with birefringent crystals and trinary polarization rotators which can rotate SOP in 3 ways.

When the rotator between two adjacent crystals rotates the SOP +45˚, the optical axes of the two crystals are aligned to produce the maximum combined DGD. When the rotator between two adjacent crystals rotates the SOP -45˚, the optical axes of the two crystals are counter-aligned to produce the minimum combined DGD. When the rotator between two adjacent crystals rotates the SOP 0˚ (no rotation), the optical axes of the two crystals are aligned 45˚ from each other, producing higher order PMD. This higher order PMD generation capability is not available in previous DGD generator designs in which the polarization rotators can only generate ± 45˚ polarization rotations. The 0 degree polarization rotation is essential for the generation of higher order PMD.

The total number of PMD values that can be generated with N+1 sections of birefringent material and N rotator pairs is 3^N. For N=8, the total number of PMD states is 6561. The total number of DGD-only (1st order PMD) states is 2^N. For N=8, the total number of DGD-only states is 256.

Unlike the analog crystal rotators used in PMD sources from other vendors, which suffer from slow speed and low repeatability, the digital ternary operation method of this PMD source makes PMD value generation fast and highly repeatable.

In addition to the digital ternary rotators described above, General Photonics' PMD source uses a quasi-continuous rotator to achieve independent DGD and SOPMD control, allowing it to uniformly cover the PMD space, as shown in Figure 7. Note that the SOPMD values generated using this method are wavelength independent, so there are no FSR issues.

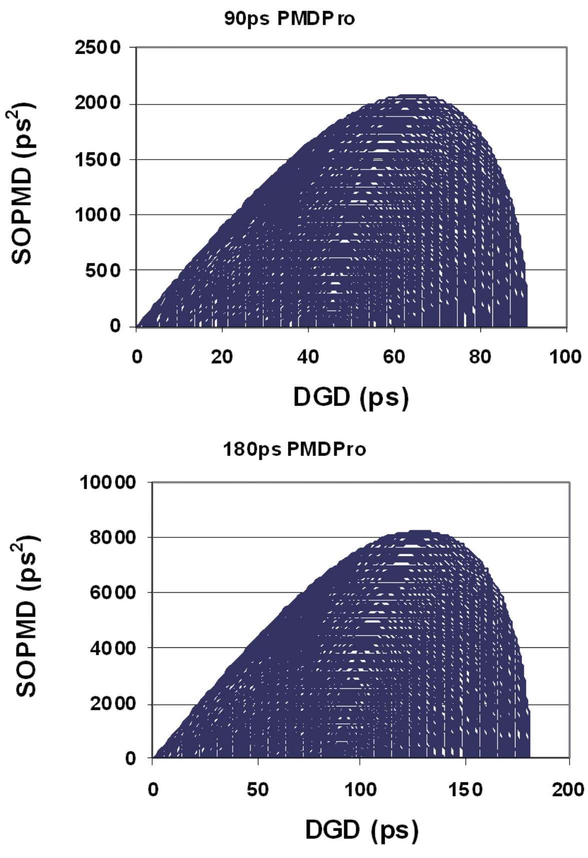

Figure 7 DGD and wavelength independent SOPMD range
A) 90 ps PMDPro™
B) 180 ps PMDPro™

Summary: Advantages and applications of the polarization optimized PMD source

The polarization optimized PMD source, constructed with digital ternary polarization rotators, offers the following attractive features for PMD related testing:

1) High precision, high repeatability PMD generation, resulting from the highly repeatable rotation angles of each ternary rotator. In its discrete digital control mode, the PMD source can generate a total of 6561 different PMD states, of which 256 are DGD-only, 1024 have DGD and wavelength independent SOPMD, and the rest are wavelength dependent PMD. In its quasi-continuous operation mode, it can generate states with independently controllable DGD and wavelength independent SOPMD values. Users can select individual PMD states or scan sequences of PMD states at user defined time intervals.

2) High PMD generation speed (minimum time interval around 1 ms), resulting from the high speed switching of the ternary polarization rotators. This high speed operation can speed up PMD tolerance tests and can be used to test the response time of a PMD compensator against sudden PMD changes.

3) Automatic optimization of input polarization for worst-case 1st order and 2nd order PMD tolerance tests, regardless of rapid polarization changes before the input to the PMD source. The polarization optimization eliminates test uncertainties and significantly reduces the time required to complete tests. It is, therefore, ideal for PMD tolerance tests for transceiver production lines, as shown in Figure 3.

4) Integrated polarization scrambler for PMD tolerance tests of coherent detection systems: Since coherent detection systems use polarization multiplexed signals, automatic polarization optimization cannot be used. Therefore, the input polarization must be scrambled to ensure that the worst-case PMD effect is achieved. The integrated polarization controller has a built-in scrambling function for this purpose.

5) PMD compensation using either an automatically optimized PMD value or a user selected PMD value. The PMD compensation is accomplished by maximizing the DOP detected by the polarimeter at the output port. Both PMD and DOP values will be shown on the front panel LCD display. By stepping the PMD values up and down and looking at the maximized DOP values, the user can directly see how the PMD value chosen affects PMD compensation. When optimized PMD mode is selected, the instrument will go through all PMD states and search for the maximum DOP. The PMD state with the maximum DOP is selected as the optimized PMD for PMD compensation.

6) PMD value determination of an in-service fiber link. The optimized PMD compensation mode can be used to determine the PMD in the link, as shown in Figure 8, because the optimized PMD value for compensation should be close to the PMD value of the fiber link. Therefore, the PMD value of a fiber link can be determined by simply inserting a polarization optimized PMD source in the light path and enabling the PMD compensation function. The optimized PMD value identified by the instrument is then the PMD value of the link. It may also be necessary to characterize the PMD of a particular channel route in an in-service ROADM network to determine its feasibility for 40G operation before installing 40G transmitters and receivers. In such a situation, an ASE source can be placed at the transmitter end

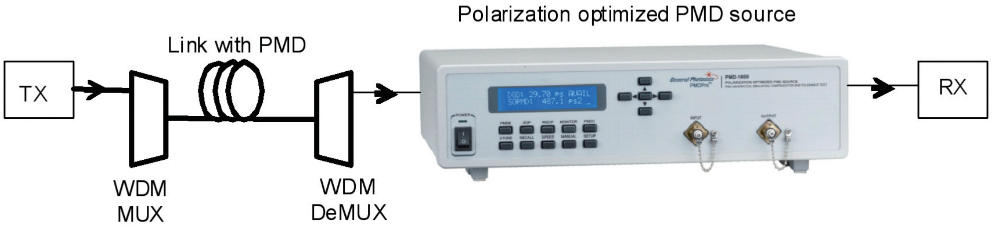

Figure 8 Polarization optimized PMD source in an in-service WDM link for the determination of its PMD and diagnosis of performance issues.

and a polarization optimized PMD source at the receiver end to perform PMD compensation. The optimized PMD value identified by the PMD source is then the PMD value of the fiber route. With this information, it is possible to decide whether the route is suitable for 40G transmission and whether a PMD compensator is required. An EDFA may be used before the PMD source to boost the signal level.

7) System impairment diagnosis. It can be difficult to identify the cause of performance problems in a fiber link. Signal degradation can be caused by PMD, chromatic-dispersion (CD), signal-to-noise ratio (SNR) issues, or other problems. Performing PMD compensation can help determine whether the problem is principally due to PMD: If PMD compensation substantially solves the transmission problem, it can be deduced that PMD is the principal cause of the problem. If not, it may be possible to rule out PMD. With such a diagnosis, it is possible to decide whether PMD compensation is required for the fiber link.

8) PMD emulation. The PMD generator can generate statistical PMD distributions to emulate PMD variations in fiber systems.

9) Polarization control functions. Using its built-in polarization controller and polarimeters, this instrument can perform all polarization control functions, including deterministic SOP generation, polarization scrambling, and polarization trace generation. It can therefore be used as a general purpose polarization synthesizer/controller for all polarization control needs.

Polarization optimization is used in the following three functions.

a. DGD tolerance test: Optimize input SOP using the SOP information from the first polarimeter as feedback to obtain the worst-case signal degradation caused by DGD.

b. PMD tolerance test: Optimize input SOP to minimize the DOP detected by the second polarimeter to obtain the worst-case signal degradation caused by both DGD and SOPMD.

c. PMD compensation: Optimize input SOP by maximizing DOP detected by the second polarimeter to minimize signal degradation caused by DGD and SOPMD.