Polarization Related Tests for Coherent Detection Systems

INTRODUCTION

Coherent detection with polarization division multiplexing (PDM) has emerged as the key technology enabler for 40 Gbps and 100 Gbps networks because it significantly increases the spectral efficiency of each channel and allows each channel to transmit at a high bit rate with relatively small optical bandwidth. Consequently, 40 Gbps, 100 Gbps, or even 160 Gbps channels can be transmitted over existing 10 Gbps WDM infrastructures with 50 GHz channel spacing [1]. PDM doubles the spectral efficiency by combining two polarization channels of the same bit rate at the same wavelength [2-8]. Also, coherent detection allows multiple levels of phase and amplitude modulation at lower rates to be multiplexed on the same wavelength channel [9-16]. For example, PDM, together with quadrature-phase-shift-keying (QPSK) modulation, enables 40 Gbps transmission within the bandwidth of a 10 Gbps direct channel [13]. At such a small bandwidth, impairments due to polarization mode dispersion (PMD) and chromatic dispersion (CD) are greatly reduced and have less impact on the bit error rate (BER) of the transmission. In addition, because both the amplitude and phase information of the two orthogonal polarizations of a signal are preserved in a coherent detection system, PMD, PDL (polarization dependent loss) and CD compensations can be performed by digital signal processing (DSP) in the electrical domain to further extend system tolerance of the effects of PMD, PDL and CD.

A system deploying polarization multiplexing must be able to separate the two polarization channels at the receiving end. Such a task can be accomplished optically by controlling polarization with a feedback signal. Because both phase and amplitude information of both polarizations are maintained during coherent detection, the information can be obtained by digital signal processing (DSP). Digital polarization demultiplexing can significantly reduce cost and size, compared with optical demultiplexing.

POLARIZATION TEST REQUIREMENTS

Coherent detection systems generally perform the following polarization control functions:

Polarization demultiplexing

PMD compensation (PMDC)

PDL compensation (PDLC)

These functions can be accomplished using high speed DSP circuits and algorithms in the transceivers. For transceiver developers, the evaluation of different DSP circuits and algorithms is critical. For the system integrators using the transceivers, it is important to compare the performance of transceivers from different vendors, including the three key polarization control functions. Finally, network operators using the systems developed by different system vendors can evaluate and compare the polarization performances from different vendors and optimize deployment decisions.

Polarization Demultiplexing Related Tests

For polarization demultiplexing, important testing parameters include:

- State of polarization (SOP) tracking speed
- SOP recovery time
- SOP orthogonality between the two polarization channels

SOP tracking speed is defined as the highest speed of SOP, measured in radians/second, at which a system can operate properly without losing track. It is a measure of how well the demultiplexing circuitry and algorithm track polarization variations of different patterns at different speeds.

SOP recovery time is defined as the time required for a system to recover from a loss of polarization track caused by an abrupt polarization change. It indicates how well the demultiplexing circuitry and algorithm respond to sudden SOP jumps.

Polarization orthogonality reflects the polarization channel crosstalk. In practice, it should be measured after two polarization channels are combined at the transmitter end and before they are separated at the receiving end. Ideally, the two polarization channels are perfectly orthogonal during transmission. However, imperfection in the polarization combiner can cause the two channels to be imperfectly orthogonal when they are combined. In addition, PMD, PDL, and nonlinearity may degrade the orthogonality of the two polarization channels and cause crosstalk. The degree of polarization (DOP) is an indication of polarization crosstalk. If there is no polarization crosstalk, the DOP is zero when the powers in the two polarization channels are equal. In the presence of crosstalk, the DOP is non-zero when the powers in the two polarization channels are equal.

PMD Related Tests

For PMD compensation, key performance indicators include SOP tracking speed, SOP recovery time, PMD tracking speed, PMD recovery time, and PMD tolerance range. Similar to their definitions in polarization demultiplexing, SOP tracking speed is defined as the highest polarization variation rate at which the PMD compensation (PMDC) hardware and algorithm can effectively reduce PMD related signal distortions, and SOP recovery time as the time required for a PMDC to recover from a loss of track caused by an abrupt polarization jump.

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. It is specified in picoseconds/second and defines how fast a PMDC can respond to PMD value changes.

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. It measures how well a PMDC responds to sudden changes in PMD.

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

PDL Related Tests

For PDL testing, the critical parameters are SOP tracking speed, SOP recovery time, PDL tracking speed, PDL recovery time, and PDL tolerance range. SOP tracking speed is defined as the highest SOP variation speed at which the PDLC can still function effectively in reducing PDL related transmission errors. SOP recovery time is defined as the time required for a PDLC to recover from a loss of track caused by an abrupt polarization change. PDL tracking speed is defined as the highest rate of PDL change (in units of dB/s) at which a PDLC can effectively reduce PDL related errors. PDL recovery time is defined as the time required for a PDLC to recover from a loss of track caused by an abrupt PDL change. Finally, PDL tolerance range is the maximum PDL value in a transmission system with which data can be transmitted with an acceptable BER. It is a measure of how well a PDLC works in mitigating PDL effects and in extending the system's PDL tolerance range.

Table I (below) summarizes the tests required for each function of a coherent detection system.

Polarization Demux	PMDC	PDLC
SOP Tracking Speed	SOP Tracking Speed	SOP Tracking Speed
SOP Recovery Time	SOP Recovery Time	SOP Recovery Time
SOP Orthogonality	PMD Tracking Speed	PDL Tracking Speed
	PMD Recovery Time	PDL Recovery Time
	PMD Tolerance Range	PDL Tolerance Range

INSTRUMENTATION

Different instruments are required to perform the various tests listed in Table I.

SOP Tracking Speed and SOP Recovery Time Tests

SOP tracking speed and recovery time tests require a polarization controller with specific capabilities.
Fig. 1 shows a test setup including the General Photonics MPC-202:

Fig. 1 SOP tracking speed and recovery time tests in a coherent detection system. The General Photonics MPC-202 can be used for these tests.

The MPC-202 Multifunction Polarization Controller (Figure 2) has four functions that are uniquely suited to these tests.

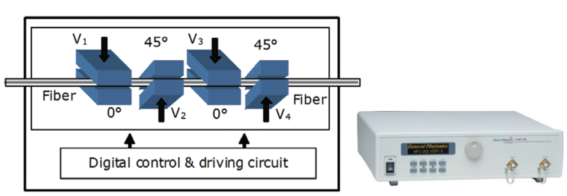
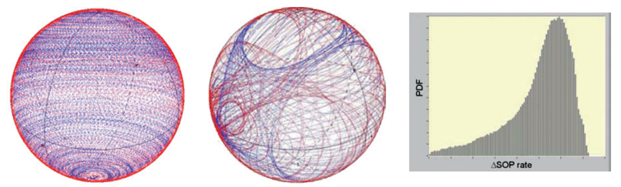


Fig. 2 Illustration of a multifunction polarization controller (MPC-202) constructed with multiple fiber squeezers.

1. Fast, Quasi-Uniform Rate Polarization Change

The new Tornado scrambling method covers the Poincaré sphere with a spiral SOP trace about a fixed or rotating axis. Unlike other scrambling methods, its polarization variation rate distribution is very narrow and concentrated at the high end of the distribution curve, a profile that greatly improves the reliability and repeatability of SOP tracking speed tests. The polarization variation rate can be up to 360 krad/s, much faster than the polarization variation found in real fiber (up to 280 krad/s). This scrambling method is therefore uniquely suited to SOP tracking speed testing.

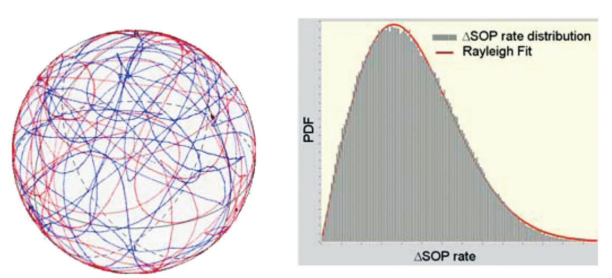


(a) (b) (c)

Fig. 3 a) Tornado SOP trace, fixed axis. b) Tornado SOP trace, rotating axis. c) Tornado scrambling SOP rate variation distribution.

2. Polarization Variation Emulation

SOP changes continuously in real fiber, as shown in Fig. 3d, with a variation rate that follows a Rayleigh distribution, as shown in Fig. 3e. The MPC-202 can generate this polarization variation pattern, with a mean rate of polarization variation that can be selected within a range of 0.01 to 2000 rad/s. This function can be used to model the effect of SOP variation in a real fiber system.



(d) (e)

Fig. 3d) SOP trace generated by the Rayleigh scrambling function.
e) Rayleigh rate distribution

3. Abrupt, Random Polarization Change

The SOP changes between discrete points distributed uniformly across the Poincare Sphere, at a rate of change ranging from 0.01 to 20,000 points/s.

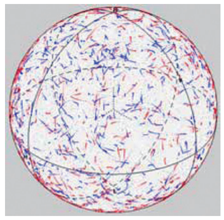


Fig. 3f) SOP points generated by the random scrambling function.

4. Generation of Polarization Variations with Waveforms

Polarization variations based on sine, triangle, and square waves of variable frequency and amplitude can be generated. Fig. 3g shows a square wave variation.

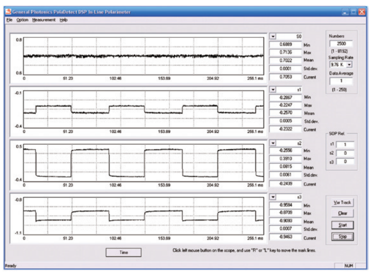


Fig. 3g) SOP traces (four Stokes parameters) generated by the square wave function, displayed on the POD-201's oscilloscope screen.

5. Triggered Random State Generation

The instrument can generate random polarization states on receipt of an external trigger signal, making it possible to test the response of the polarization tracking circuit/algorithm under test to a series of step polarization changes.

The MPC-202's square waveform function is a particularly useful tool for recovery time characterization because it generates an abrupt SOP transition of controllable magnitude at controllable intervals. The maximum slew rate for a square wave polarization modulation is 360 krad/s, more than sufficient to emulate the fastest polarization transitions in real fiber.

Figure 3h shows a circuit recovery time measurement using a square wave-induced change in SOP. The sharp rising edge causes the polarization tracking circuit to lose track before recovering.

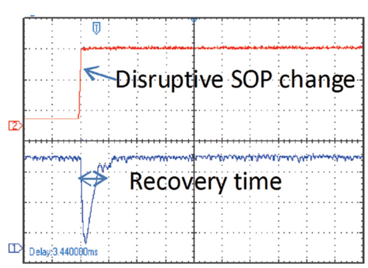


Fig. 3h) Tracking circuit recovery from disruptive SOP change (square wave transition).

Instruments that rely on mechanical motion, such as the Agilent model 11896A Polarization Controller, are bandwidth limited. For example, the Agilent unit can only generate variations up to three hertz, which may not be adequate for testing modern systems.

However, because the Agilent 11896A was the first mainstream polarization controller available, many engineers are familiar with and rely on its polarization scrambling characteristics. For compatibility with this early standard, the MPC-202 has an Agilent 11896A emulation function that replicates the scrambling function of the Agilent polarization controller.

Polarization Orthogonality Test

The SOPs of the two polarization channels should ideally be orthogonal in the transmission fiber from the time that they are combined (or multiplexed) by a polarization beam combiner (PBC) at the transmission side until they are separated (or demultiplexed) by a polarization beam splitter (PBS) at the receiving end. Imperfections in PBCs can cause non-orthogonality, and standard specifications, such as polarization extinction ratio (PER), do not always properly reflect the orthogonality performance of the PBC; special tests are therefore required.

Two General Photonics instruments can be used for testing the orthogonality of a PBC: the POD-201 in-line polarimeter and the PSGA-101A polarization measurement system (Figure 4).

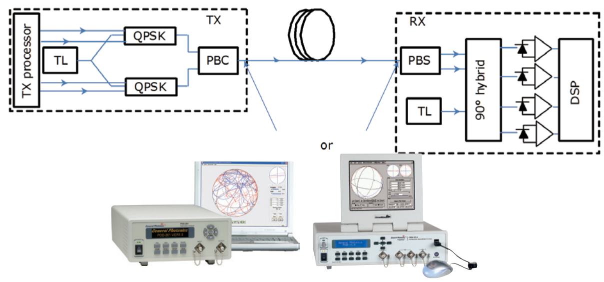
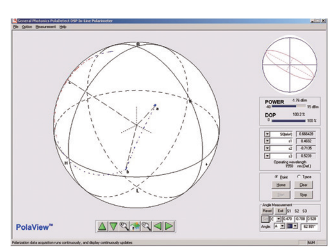


Fig. 4 SOP orthogonality test of two polarization multiplexed signals at the output of the polarization beam combiner (PBC) and at the input of the polarization beam splitter (PBS) in a polarization multiplexed coherent detection system. The POD-201 or the PSGA-101 can be used for the test.

During the test, the polarization channels are sequentially turned "off" and the SOP of the "on" channel is measured. The relative polarization angle between the two SOP points is obtained through the angle measurement function of the software. A relative angle of 90 degrees indicates perfect orthogonality, and the amount of deviation from 90 degrees of the actual angle is a measure of non-orthogonality.

Polarization orthogonality may also degrade during transmission due to the effects of PMD, PDL, or nonlinearity. Again, both the POD-201 and PSGA- 101 can be used to quantify the degradation by using the measurement method described above before the PBS at the receiver side.



PolaView™ angle measurement function for testing SOP orthogonality.

PMD Tracking Speed and PMD Recovery Time Tests

For PMDC using DSPs in a coherent system, the circuit/algorithm must track SOP variations and rapid PMD changes. In order to test a PMDC's PMD variation tracking speed and PMD recovery time, an instrument with fast PMD generation capability is required. The General Photonics PMDPro™ is recommended for these tests.

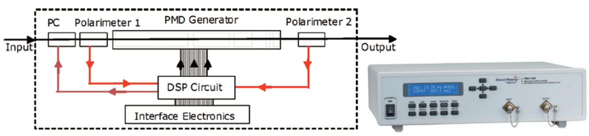


Fig. 5 Illustration of PMDPro™ polarization optimized PMD source. Its PMD generator can generate 1st and 2nd order PMD in less than 1 ms. The polarization controller (PC) is used to generate different SOP variations as in the MPC-202. In addition, the PC, together with the two polarimeters, is used to perform polarization optimization functions as well as polarization synthesis functions.

The PMDPro™ consists of a polarization controller, a front polarimeter, a PMD generator, and a rear polarimeter (Figure 5). The polarization controller can be used with the front polarimeter to automatically align and maintain the input SOP at 45˚ from the principal axis of the DGD element to obtain the worst-case first-order PMD effect. Alternatively, the controller can automatically adjust and maintain the input SOP using the feedback from the rear polarimeter to either minimize or maximize the output DOP for each PMD setting. Minimizing the output DOP enables testing of the worst-case total PMD effect, while maximizing the DOP turns the PMDPro™ into a PMD compensator, allowing the user to measure the PMD values of an active fiber link.

The PMDPro™ can also perform PMD emulation by generating statistical PMD distributions. Finally, the polarization controller and polarimeters can provide various polarization control functions, including variable rate polarization scrambling, polarization waveform generation, polarization trace generation and polarization stabilization at any SOP.

The PMD generator inside the PMDPro™ can deterministically generate both 1st and 2nd order PMD (SOPMD) values in a few milliseconds because the all digital design utilizes no mechanical rotators. Figure 6 shows available values of DGD and SOPMD.

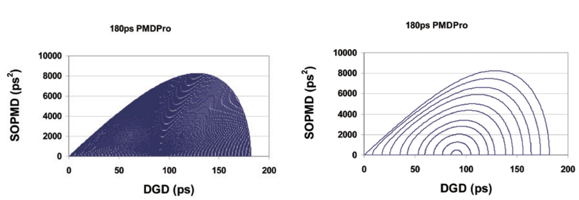


Fig. 6 The left plot is a comprehensive map of DGD vs. 2nd order PMD (SOPMD), showing the coverage of generated PMD values with dense (256) PMD traces. The right plot shows some typical PMD traces. PMD values can be varied quickly along those traces.

Different operation modes provide different PMD change patterns for the two different tests: For PMD recovery time testing, the discrete PMD generation mode allows the user to change PMD values discontinuously with user selected step sizes and dwell times. The abrupt PMD jump offered in this mode will cause loss of track in the PMDC and enable the user to measure the time required for the PMDC to regain track. For PMD tracking speed testing, the continuous PMD generation mode allows the user to vary PMD values along a trace like those shown in the second graph in Fig. 6. Operators can gradually increase the PMD variation speed until the PMDC can no longer follow.

PMD Tolerance Test

Coherent Detection systems use DSP to increase PMD tolerance. PMD tolerance tests measure the maximum PMD value that the system can tolerate. A typical test setup is shown in Fig. 7a.

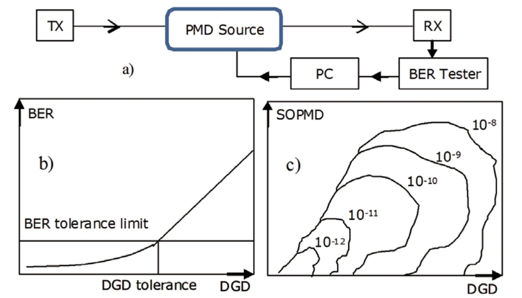


Fig. 7 a) PMD tolerance test setup using a PMDPro™ PMD source. The computer (PC) selects PMD settings and collects BER readings. b) A BER vs. DGD curve can be obtained, and the DGD tolerance for a given BER threshold can be deduced using the curve. c) Map of BER vs. DGD and SOPMD. Each contour represents a BER value, and the PMD tolerance can be obtained from the contour plot.

Test results can be used by network operators to compare systems made by different vendors and verify PMD related specifications promised by the vendors. They can also be used by system vendors to determine suitability of PMD algorithms, to tune algorithms, and for quality control screening of the transceivers. The key instrument in this setup is the PMD source used to generate precise 1st and 2nd order PMD values, as shown in Fig. 7a. The bit-error rate (BER) of the system, or another performance indicator parameter such as power penalty, is monitored as the 1st order PMD (DGD) values generated by the PMD source are increased until the BER reaches the limits of the system, as shown in Fig. 7b. 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 Fig. 7c. The system outage probability can be calculated from the data obtained.

The effect of PMD on a system is highly dependent on the input SOP. To eliminate test uncertainties and increase test speed, the input SOP must be optimized and maintained against polarization fluctuations caused by external disturbances. For a single polarization system without multiplexing, the PMDPro™ has two modes of polarization optimization for PMD tolerance tests. One mode aligns the input SOP 45 degrees from the principal axes of the DGD generator to obtain the worst-case DGD effect. The second mode aligns the SOP by minimizing the output DOP to obtain the worst-case total PMD effect on the signal. Polarization optimization assures consistent and repeatable PMD tolerance test results.

In polarization multiplexed systems, where two orthogonal polarization channels are present simultaneously, the PMDPro™'s polarization optimization functions are not useful; however, the built-in polarization scrambling functions can be used to scan through all possible polarization states to assure that the worst-case polarization effects are properly characterized.

Polarization Dependent Loss (PDL) Tolerance Test

A coherent detection system generally includes hardware and algorithms to compensate for the effects of PDL (PDLC). System vendors and operators need to know how much PDL a transceiver can tolerate, and therefore must conduct tolerance range testing. A system vendor can use test results to optimize hardware and algorithms, and to perform quality checks. Network operators can use PDL tolerance range testing to qualify vendors and to perform quality inspection of incoming equipment to ensure the performance of their systems.

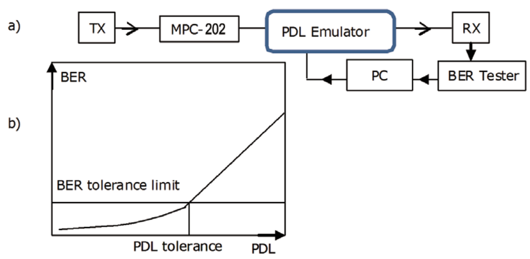


Fig. 8 a) PDL tolerance test setup. b) A typical BER vs. PDL curve

Fig. 8a shows a typical setup for measuring the PDL tolerance of a transceiver or system. A PDL emulator capable of generating any PDL value is essential for conducting a PDL tolerance range test. The PDL tolerance range can be determined from the BER vs. PDL graph, as shown in Fig. 8b. Because PDL effect on the signal is sensitive to SOP variation, an MPC-202 can be placed in front of the PDL emulator/source to generate the required SOP variations.

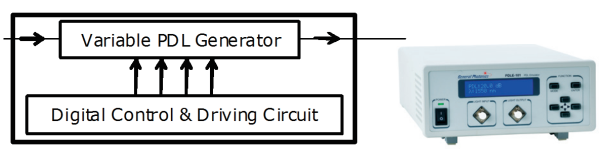


Fig. 9a) Construction and photo of PDLE-101.

General Photonics' PDL emulator, the PDLE-101, is designed for PDL related system tests, particularly PDL tolerance testing. The emulator can set any PDL value from 0 dB to 20 dB with a speed of less than 5 ms and a resolution of 0.1 dB. The PDL value can be set individually or can be scanned with a user defined range, waveform, and speed. In addition, random PDL variations can be generated to emulate PDL variations in a real system.

PDL Tracking Speed and Recovery Time Tests

PDL changes rapidly with time in real systems. It is therefore important to evaluate whether the PDL compensation can track the PDL changes. In order to test the PDL tracking speed of the PDL compensation, an instrument to generate fast PDL variations is essential. The PDLE-101's ability to generate PDL changes using different wave forms is uniquely suited to such an application. Fig. 9b shows such a PDL variation following a triangle wave modulation.

The PDLE-101 can also generate abrupt PDL jumps in the form of a square wave, as shown in Fig. 9c. The abrupt PDL jump can cause the PDLC to lose track of the PDL, enabling the measurement of the time required for the PDLC to regain track for PDL compensation.

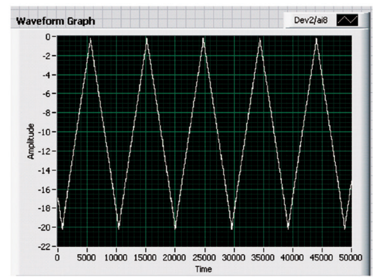


Fig. 9b) Triangle wave PDL variation

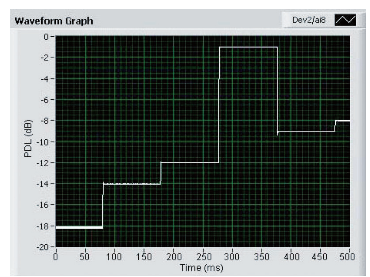


Fig. 9c) Random amplitude square wave PDL variation

Component Level PMD/PDL Measurements

The General Photonics PSGA-101A is recommended for characterization of PMD and PDL for component testing [17]. As shown in Fig. 10, the PSGA-101A consists of a tunable laser, a binary polarization state generator (PSG), a binary polarization state analyzer (PSA), and an internal computer.

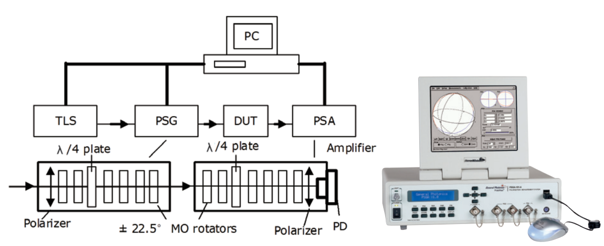


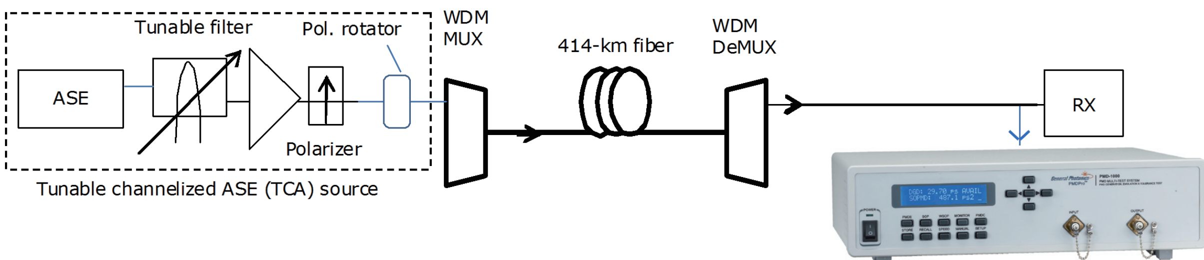
Fig. 10 Illustration of a PSGA-101A polarization analysis system based on a novel binary polarization analysis method which enables very high accuracy and repeatability.

The binary magneto-optic polarization rotator design of the PSGA provides measurement accuracy that can only be calibrated with NIST grade material standards. The values in the table below exceed those of any other instrumentation product on the market by an order of magnitude.

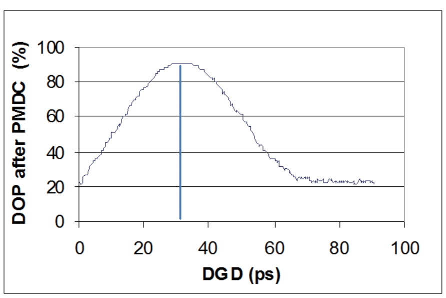
	DGD (1st Order PMD)	SOPMD (2nd Order PMD)	PDL
Accuracy	± 2.6 femtoseconds	± 1.39 ps^2	± 0.06 dB
Resolution	1 femtosecond	0.005 ps^2	0.01 dB
Repeatability	0.022 femtoseconds	0.28 ps^2	0.034 dB

In-Circuit Link PMD Measurement

It is often desirable to be able to measure the PMD of a transmission link without interrupting signal transmission. The General Photonics PMDPro™ has an in-service PMD measurement function, which is accomplished by PMD compensation, as shown in Fig. 11. On the Tx side, a polarized broadband light source, centered on an ITU grid with a 3-dB bandwidth of 0.25 nm and obtained by passing an ASE source through a tunable filter, is fed into an idle channel at the multiplexer. On the Rx side, the test signal is dropped out from the demultiplexing port and passes through a PMDPro™. The instrument generates DGD values between 0 and 90 ps with an incremental step of 0.357 ps. The time required to run one step is less than 1 ms. At any DGD value, PMD compensation can be performed by feeding the DOP value to the DSP circuit for it to control the polarization controller to maximize the DOP. To measure the PMD of the light path, the DGD value generated by the compensator steps from zero to its maximum value, while PMD compensation is performed by maximizing the DOP for each step. When the test signal reaches its peak DOP value, as shown in Fig. 11b, the DGD value of the compensator at this point is equal to the PMD value of the light path.



(a)



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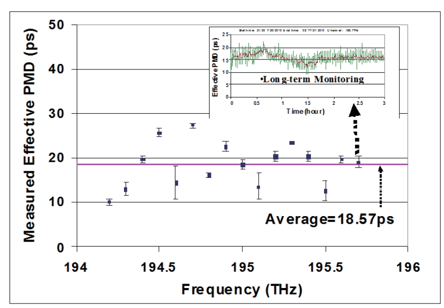


(c)

Fig. 11 In-service PMD measurement using a PMDPro™. a) System measurement setup. b) DOP vs. DGD curve. The DGD value corresponding to the DOP peak is the instantaneous effective PMD of the DWDM channel under test. c) Average PMD of the fiber link obtained by averaging instantaneous PMD of multiple DWDM channels measured at about the same time. Insert of c) shows the long term PMD monitoring result of a single channel.

General Photonics engineers demonstrated this in-service PMD characterization in a traffic carrying long haul network at a Verizon facility. The expected mean DGD of the route was calculated from the mean DGD values of the individual fiber sections using commercially available PMD measurement equipment before the long-haul system was installed and before traffic commenced. The calculated value was 19.77 ps. The length of the route is 414 kilometers with a ROADM at each end.

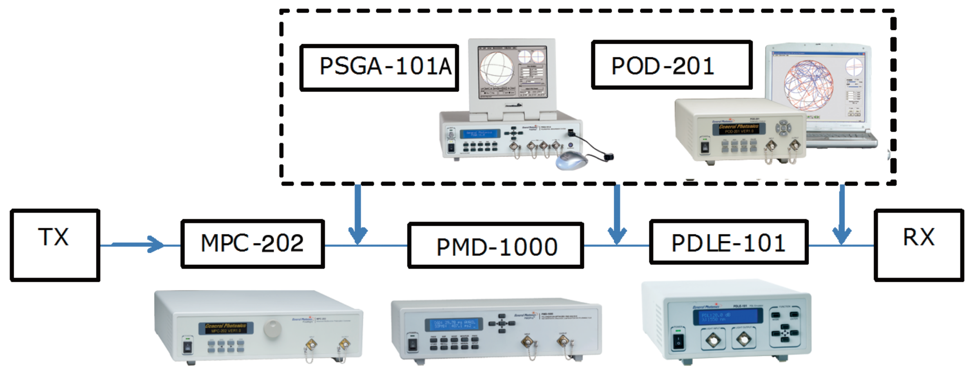
In the trial, the PMD values of 16 idle channels were measured. Figure 11c shows the measured DGD values of the 16 channels with error bars. The DGD value averaged over all 16 channels is 18.57 ps, which is very close to the expected mean DGD value of 19.77 ps. Considering the limited number of data points (channel numbers), the 6% difference between this result and the aforementioned "expected mean DGD" falls within the fundamental Gisin uncertainty [10].

The insert of Fig. 11c shows the results of a long-term PMD measurement of a single DWDM channel at 195.7 THz. Fairly stable PMD values for the channel were observed during the measurement period, taken around midnight. Note that the time average of single channel PMD for a much longer time can also yield the average PMD of the fiber link. The trial results show that the instrument is sufficiently accurate in PMD measurement, and that the measurement has no impact on the live traffic of other signal carrying channels.

We also successfully demonstrated the PMDPro™'s PMD measurement by PMD compensation function at Verizon's 1500 km test bed using a 40Gbps signal itself as the signal source for the test with a DWDM channel for about 12 hours. The average PMD result obtained was very close to the expected value of the link. This result verified the usefulness of the PMDPro™ for the monitoring of the PMD of a fiber link over an in-use DWDM channel.

Summary

Coherent detection systems for 40Gbps and 100Gbps use digital signal processing for polarization demultiplexing, PMD compensation, and PDL mitigation. To quantify the performance of those functions, multiple tests are required. The first column of Table II (below) lists some polarization related tests of coherent detection systems. General Photonics provides an array of instruments, listed in the first row of Table II, to facilitate those tests. The applicability of each instrument to particular tests are checked in the table.



	Multifunction Polarization controller MPC-202	In-line polarimeter POD-201	PMD source PMD-1000	PDL source/ emulator PDLE-101	Polarization measurement system PSGA-101A
SOP tracking speed test	Yes	Yes	Yes		
SOP recovery time test	Yes	Yes	Yes		
SOP Orthogonality		Yes			Yes
SOP & DOP viewing and monitoring		Yes	Yes, but no graphic display		Yes
PMD tracking speed test			Yes		
PMD recovery time test			Yes		
PMD tolerance range test			Yes		
PDL tracking speed test				Yes	
PDL recovery time test				Yes	
PDL tolerance range test				Yes	
PMD/PDL measurement			Yes, in-service link		Yes

References

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