TESTING POLARIZATION MODE DISPERSION (PMD) IN THE FIELD

By Gregory Lietaert, JDSU Product Manager

Introduction

Competitive market pressures demand that service providers continuously upgrade and maintain their net-works to ensure they are able to deliver higher speed, higher quality applications and services to the customers. This requires verifying and ensuring that the network's fiber infrastructure and equipment can meet exacting performance standards and operate reliably. Due to the increased transmission speed and implementation of DWDM systems, some important changes were made in the optical fiber characterization and system turn-up, requiring new test tools and procedures, described in different JDSU white papers.

Polarization Mode Dispersion (PMD) testing is becoming essential in the fiber characterization process, but still one of the most difficult parameter to test, due to its sensitivity to a number of environmental constraints.

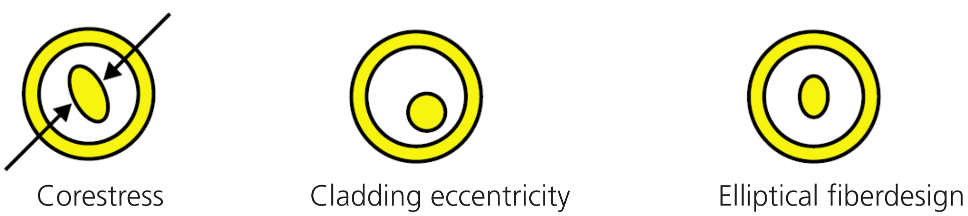
Polarization Mode Dispersion definition

PMD (Polarization Mode Dispersion) is caused by the differential arrival time of the different polarization com¬ponents of the input light pulse, transmitted into an optical fiber. This light pulse can always be decomposed into pairs of orthogonal polarization modes. These polarization modes propagate at different speeds according to a slow and fast axis induced by the birefringence of the fiber.

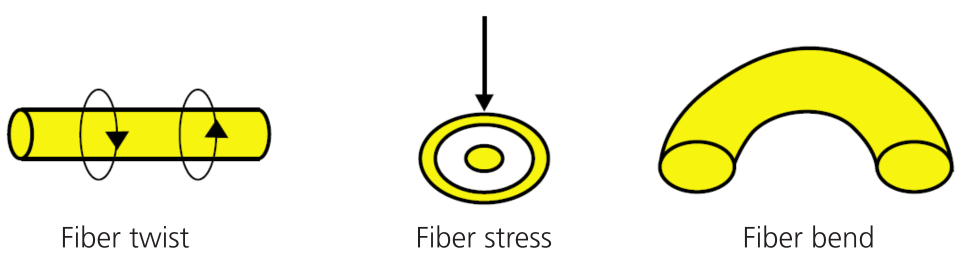
Bi-refringence

Optical fibers are slightly bi-refringent. Bi-refringence is a property of material (e.g. optical fiber) where the effec¬tive index of refraction varies with the polarization state of the input light.

The main causes of this bi-refringence are non-perfect concentricity and in homogeneity of the optical fiber in manufacturing design, as well as external stresses applied on the fiber cabling, such as bends, or twist.



Imperfect fiber design causes bi-refringence



External stress causes bi-refringence

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Differential group delay

In a single mode fiber, light is guided through the whole core and in a part of the cladding (referring to Mode field diameter), so that there is only a single propagation mode. However, as fibers are birefringent materials, this propagation mode, is polarized in two different ways, following the polarization axis of the fiber (These axis are also called Principal States of Polarization -PSP-). This leads to two polarization modes.

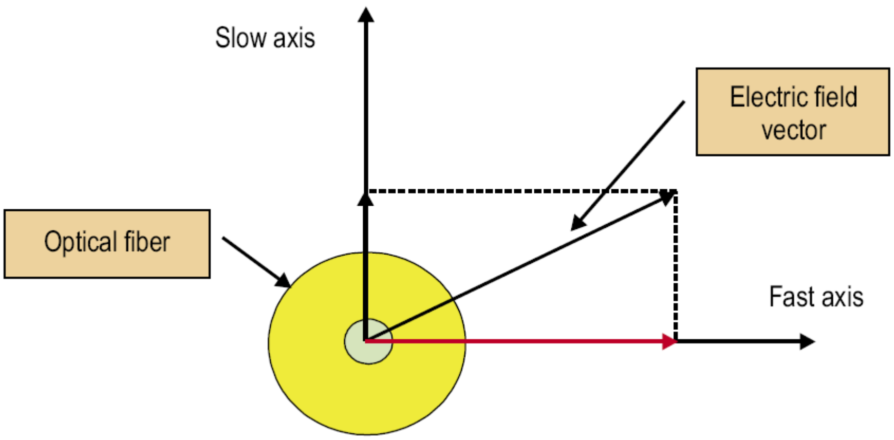

Figure 1: Electrical field vector decomposed into two polarization modes (fast and slow)

As any birefringent material, there is a difference of refractive index value between the two PSP, which means that there is a fast PSP and slow PSP.

These slow and fast propagation axis, create a variation in the propagation speed of the orthogonal pair of polarization modes of the light, presenting a different time arrival at the receiver side. This time difference is the Differential Group Delay (DGD), so called PMD delay.

A light pulse transmitted through a "uniform", Highly Birefringent (HiBi) or polarization maintaining, fiber could be defined as the decomposition of the pulse into 2 orthogonal pulses (see figure 1) travelling at different, but constant speed.

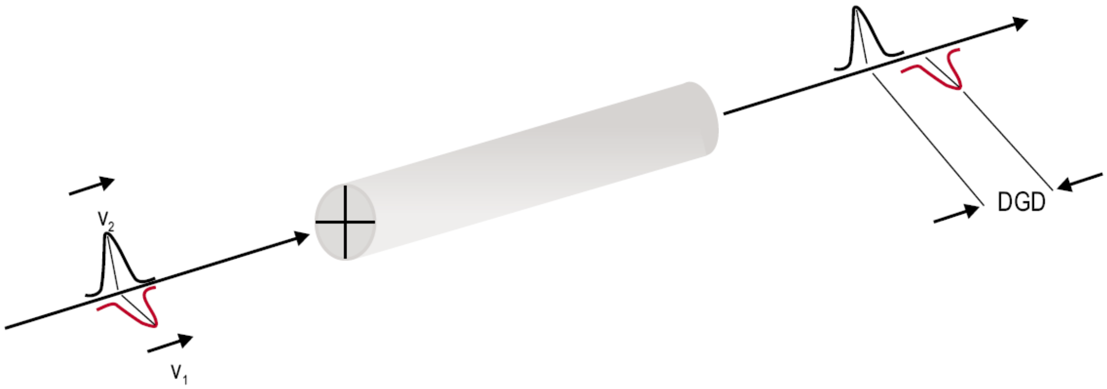

Figure 2: Differential group delay in HiBi fiber

However, in telecommunication optical fibers, birefringence levels and principal axis are not uniform over the total link, and could be considered as the result of HiBi fibers randomly coupled together.

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As a consequence, there is a polarization mode coupling between fast and slow modes each time the principal states of polarization orientation changes. This is called a strong mode coupling.

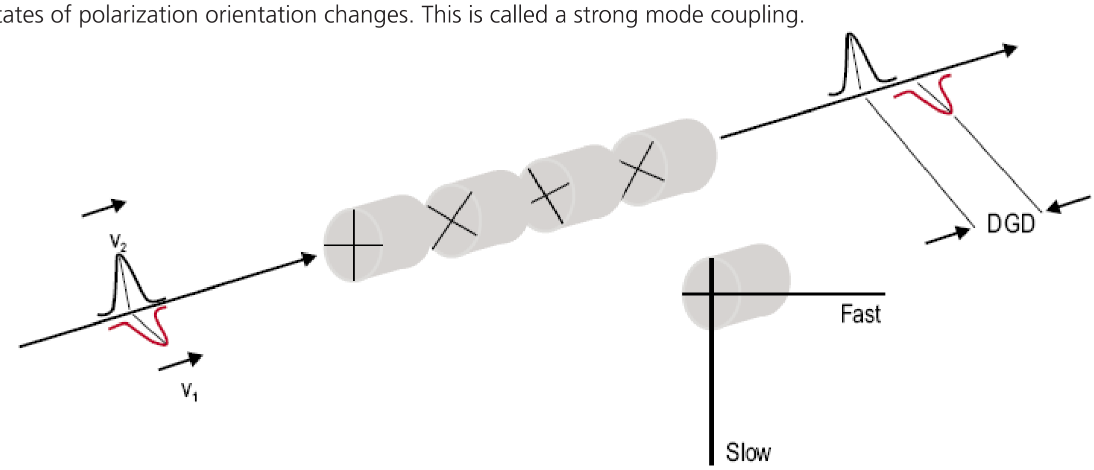

Figure 3: Strong mode coupling in telecommunication fibers

The speed of light in strong mode coupling fiber depends, obviously, on the input state of polarization (even such a complex system has a slow and fast Principal State of Polarization), but also on the way of polarization light rotates according to the wavelength: The State of Polarization, as well as the delay between the fast and slow axis, is dependent from the wavelength.

The function of DGD vs. wavelength is constantly changing (figure 6). The biggest factor affecting this function is temperature. Only a few degrees of variation is enough to completely skew the data. In addition, any human intervention on the fiber link, changing the fiber layout, will have the same consequences.

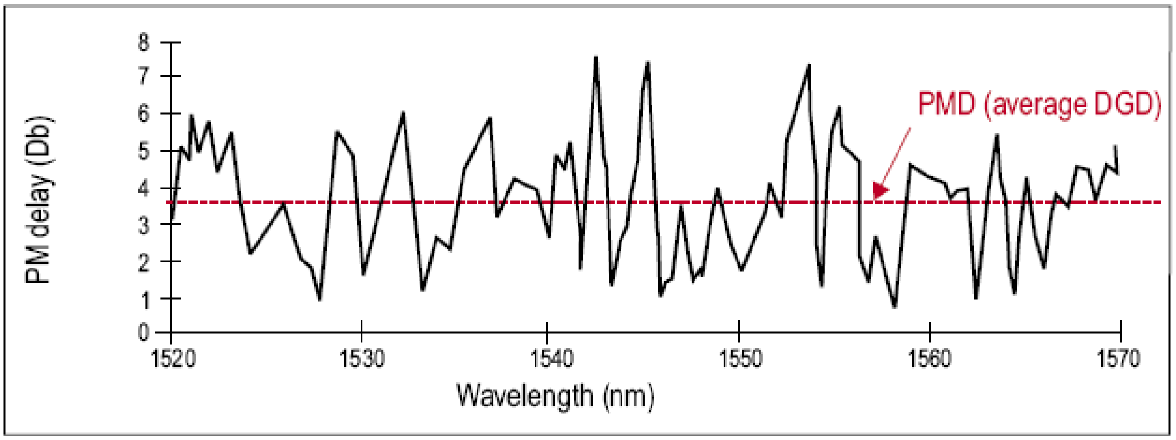

Figure 4: DGD variation over a wavelength range

"From [the] data. DGD varies slowly over time but rapidly over wavelength…data showed good agreement with a Maxwellian distribution. The frequency averaged mean DGD [emphasis added] varied about 10% or less during periods that showed significant temperature swings"

Analysis and comparison of measured DGD data on buried single-mode fibers. Allen et. al2002

As PMD depends on random optical fiber's birefringence, it cannot be characterized directly: The instantaneous DGD cannot be used directly, because it does not have a reproducible value. DGD values fluctuate randomly around an average (mean) value, describing a Maxwellian curve, as shown on the figure 3.

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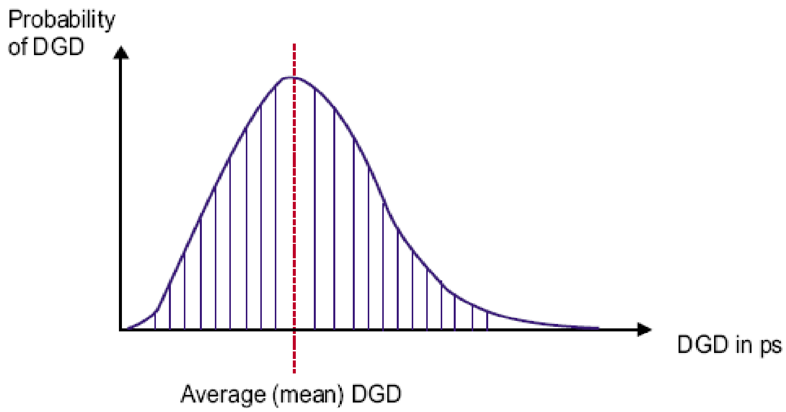

One commonly accepted parameter to be measured in order to characterize the PMD delay is the mean DGD across a certain wavelength range. The mean DGD is the efficient value of the differential group delay density of probability of the total fiber link, it is called the PMD delay, expressed in [ps].

Doubling the mean DGD, the fiber length had to be increased by a factor 4; and that to triple the DGD, it had to be increased by a factor 9. So "the average DGD scales as the square root of the length of the fiber."

The polarization mode dispersion is defined with up to four main parameters:

- PMD delay [ps] or mean DGD
- PMD coefficient
- Second order PMD delay or DGD2 [ps/nm]
- Second order PMD coefficient (PMD2, in ps/(nm.km)).

Second order PMD

The second order PMD gives the delay created by the PMD variation linked to the wavelength, and therefore is interesting for DWDM and very high speed transmission systems. It provides the indication of the wavelength dependency of the PMD delay.

- rate of change of DGD vs Wavelength
- It describes the change of direction of PSPs

Second order PMD has to be added to chromatic dispersion figures, and therefore is limiting the link distance.

Why does PMD appear?

Several factors are involved in the generation of PMD. Fiber optic cables which have been employed in the outside plant are not perfect.

- Manufacturing defects.
  - The fiber core is not perfectly circular along its overall length
  - The fiber core is not perfectly concentric with the cladding
  - The fiber can be twisted or bent at some points along the span.
- PMD constraints increase with:
  - Channel bit rate
  - Fiber length (number of sections)
  - Number of channels (increase missing channel possibility)

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- PMD decreases with:
  - Better fiber manufacturing control (fiber geometry)
  - PMD compensation modules
- PMD is more an issues for old G.652 fibers (<1996) than newer G.652, G.653, G.655 fibers

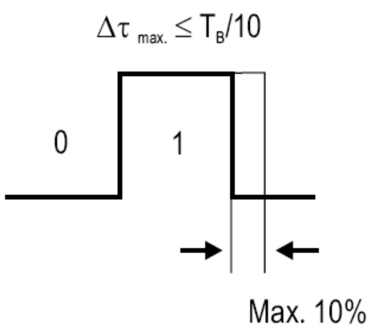
At any given signal wavelength the PMD is an unstable phenomenon, unpredictable. Instantaneous PMD varies with λ, time, T°, movement. PMD is not intrinsic and requires statistical predictions as it fluctuates over the network life cycle.

Limiting fiber parameter

The mean DGD causes the transmission pulse to broaden when traveling along the fiber, generating distortion and increasing bit-error-rate (BER) of the optical system. The consequence is limitation of the transmission distance for a given bit rate.
If the maximum PMD delay is known, the maximum admissible fiber length can be deduced.

L = Δτ2/Δτc max2

The statistical character of the PMD is taken into account where defining the maximum tolerable PMD delay as 10% of the bit length TB for a system, without disturbing the network performance by more than 1 dB loss, at 1550 nm, with NRZ coding



Considering a transmission speed of 10 Gb/s, the bit length (100 ps) can be determined and then used to calculate the theoretical maximum PMD delay: Δτ = 0.1 * 100 ps = 10 ps
In practice, some systems can accept up to 13-14 ps, depending on the coding structure.
The result of this calculation according to different transmission speeds is summarized in the table below.

Bit rate per channel	SDH	SONET	Equivalent timeslot	PMD delay limit	PMD coefficient with 400 km
55 Mb/s	——	OC-1	19.3 ns	2 ns	<100 ps/√km
155 Mb/s	STM-1	OC-3	6.43 ns	640 ps	<32 ps/√km
622 Mb/s	STM-4	OC-12	1.61 ns	160 ps	<8 ps/√km
1.2 Gb/s	——	OC-24	803 ps	80 ps	<4 ps/√km
2.5 Gb/s	STM-16	OC-48	401 ps	40 ps	<2 ps/√km
10 Gb/s	STM-64	OC-192	100 ps	10 ps	<0.5 ps/√km
40 Gb/s	STM-256	OC-768	25.12 ps	2.5 ps	<0.125 ps/√km

This PMD limits are used to determine the maximum admissible fiber length.
You will find below, for a typical transmission system, the maximum PMD coefficient as a function of length, at a given transmission bit rate.

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This graph is provided with the following assumptions: The PMD is considered to be Maxwellian, NRZ coding is used, 1550 nm lasers are used, a maximum power penalty of 1 dB is acceptable, a BER is typically between 10-9 and 10-12. With this in mind, the following formula could be applied (L is the distance in km, B the bit rate in Gb/s, PMD the PMD value in ps/√km:

$$L = \frac{10^4}{(B*PMD)^2}$$

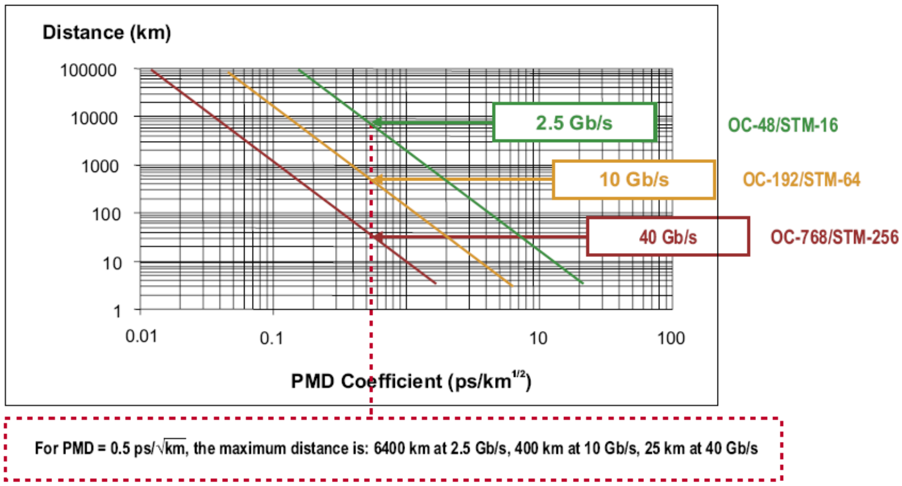

Figure 6: Maximum distance vs. PMD coefficient and data bit rate

When testing PMD?

PMD testing is becoming a requirement when the transmission bit rate per channel rises or with the increase of the corresponding distance. It appears that the measurement shall be at least performed when the bit rate is equal or higher than 10 Gb/s. However, for fibers older than 1996 or for some applications, such as analog cable TV applications, lower transmission bit rates will be affected by PMD.

As a summary, the main circumstances in which PMD measurement will be required are:

- Qualification during fiber manufacturing
- Qualification during cable manufacturing
- Installation of new fiber networks, for 10 Gb/s bit rate or higher.
- Installation of ultra long haul networks at 2.4 Gb/s or higher
- Upgrade of current networks for 10 Gb/s bit rate or higher

Fiber and cable manufacturers are specifying their fibers with 0.5 ps/√km maximum, according to the ITU-T recommendations. However, current manufactured fibers are easily better than 0.2 .ps/√km

As PMD is a statistical measurement and, because it is sensitive to external environment, it is recommended to perform different measurements at different time intervals so that long term fluctuation of DGD can be monitored, providing better records of the fiber cable.

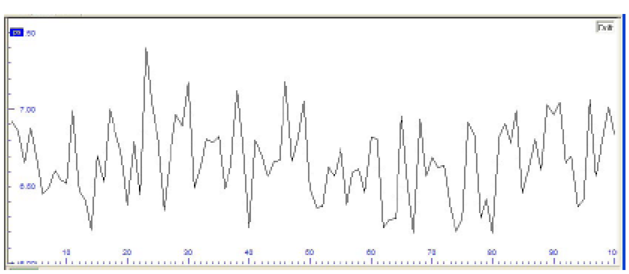

Figure 7: Drift representation of a long-term PMD delay measurement

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High PMD Values

If the PMD measurement is higher than the tolerable limit for a given bit rate, the fiber is classified as "sensitive" to PMD for that particular transmission speed. For a passing PMD result (within the tolerable limit) at a given bit rate, the fiber cannot be classified as "non-PMD sensitive". Instead, it should be classified as "suitable for the particular transmission rate" at the given time.

Currently, there is no simple and low-cost component that allows for the correction of a link with a high PMD value. Although there are a number of components under qualification and development, at this time, very few PMD compensators have been deployed in the field.

PMD is clearly important in limiting the distance (or the transmission bit rate) for a given network application. Therefore, several solutions have been developed that allow for the compensation of the effect of PMD on the transmission link, including transmitting over shorter distances, transmitting at lower bit rates per wavelength, using low chirp lasers, using dispersion-managed RZ optical soliton transmission, or using forward error correction (FEC) transmission.

PMD compensation techniques

It is particularly difficult to counteract PMD because of its statistical nature and its variation over the time and wavelength. The stochastic nature of PMD is such that, reducing the impact of PMD does not necessarily imply the complete cancellation of the effect, but the reduction of the outage probability due to PMD: This process is called PMD mitigation.

Several PMD compensation techniques have been proposed in the past few years. They can be classified into two main categories:

- Electrical PMD compensation
- Optical PMD compensation

Electrical compensation of PMD involves equalizing the electrical signal after the photodiode. This equalization can be implemented in many ways: transversal filter (TF), non-linear decision feedback equalizer (DFE), phase diversity detection. Electrical compensation schemes, in general, are robust and will improve the signal against all kinds of transmission impairments. On the other hand, they do not perform as good as optical PMD compensators and also they require high-speed electronics for better performance.

Optical PMD compensation is aimed to reduce the total PMD impairment caused by the transmission fiber and the compensator. The block diagram of a general optical PMD compensation scheme is shown in Figure 8. It has an adaptive counter element, a feedback signal and a control algorithm.

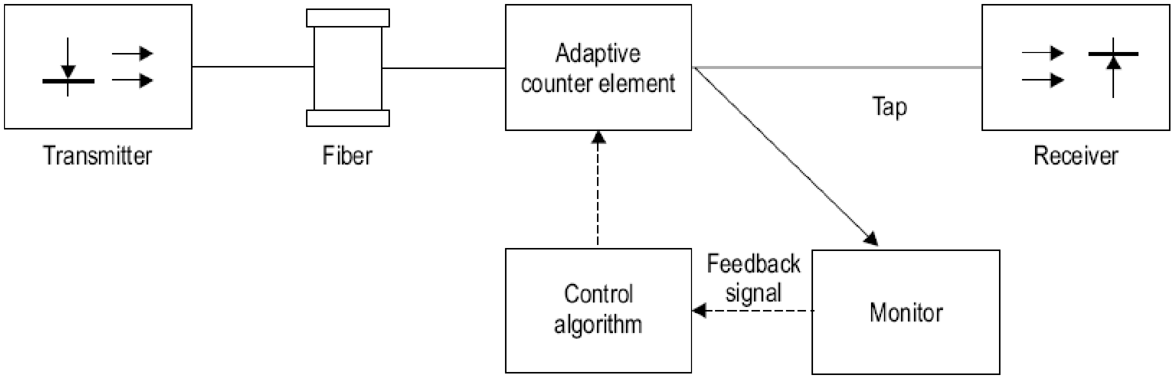

Figure 8: General scheme for optical PMD compensation

The adaptive counter element is the core of any PMD compensator. It must be able to counteract PMD impairments and be tunable. The feedback signal is required to provide the PMD information to the controlling algorithm of the compensator.

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PMD international standards and recommendations

Standards such as ITU-T, IEC and TIA/EIA, have provided guidelines and recommendations related to PMD and its associated measurements. You will find below a list of the main references related to PMD.

Standards	Description
ITU-T G.650.2	Definition and test methods for statistical and non linear attributes of single-mode fiber and cable
ITU-T G.652	Characteristics of a single-mode optical fiber and cable
ITU-T G.653	Characteristics of a dispersion-shifted single-mode optical fiber and cable
ITU-T G.654	Characteristics of a cut-off shifted single-mode optical fiber and cable
ITU-T G.655	Characteristics of a non-zero dispersion-shifted single-mode optical fiber and cable
ITU-T G.656	Characteristics of a fiber and cable with non-zero dispersion for wideband transport
IEC/TS 61941	Technical specifications for polarization mode dispersion measurement techniques for single-mode optical fibers
IEC 60793-1-48	Measurement methods and test procedures - Polarization mode dispersion
GR-2947-CORE	Generic Requirements for Portable Polarization Mode Dispersion (PMD) Test Sets
TIA/EIA-455 FOTP-113	Polarization Mode Dispersion Measurement for Single-Mode Optical Fibers by the Fixed Analyzer Method
TIA/EIA -455- FOTP-122A	Polarization Mode Dispersion Measurement for Single-Mode Optical Fibers by Stokes Parameter Evaluation
TIA/EIA -455- FOTP-124A	Polarization Mode Dispersion Measurement for Single-Mode Optical Fibers by Interferometry
TIA/EIA TSB 107	Guideline for the Statistical Specification of Polarization Mode Dispersion on Optical Fiber Cables

PMD Test methods description

As described in the test and measurement standards, there are different ways of measuring PMD in the field. Only four methods will be described below. Other methods exist but are dedicated to for production/lab testing (Poincaré Sphere, State of Polarization, modulation phase shift, pulse delay, time delay and the base-band curve fit methods).

The first 3 methods below are classified following the IEC-60793-1-48 international standard, where GINTY method is not an IEC standardized method yet published. All test methods are also published by the ITU-T G650.2. The EIA/TIA provides a recommendation for each individual test solution.

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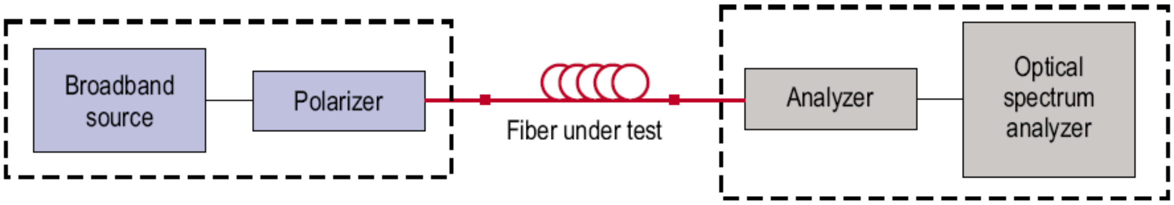
Method A – Fixed Analyzer (also known as wavelength scanning)

Equipment

This method requires the following devices:
- A broadband polarized source
- A polarized (variable) optical spectrum analyzer (OSA).



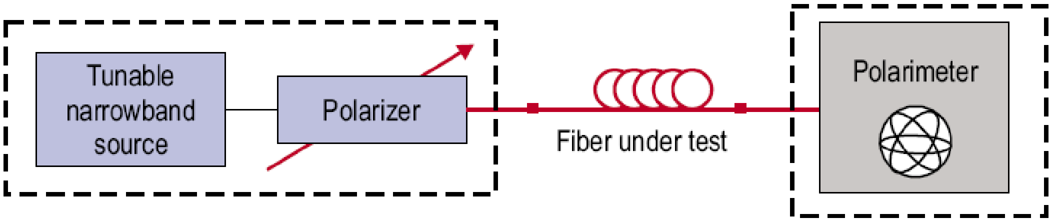
Principle

From the power fluctuations spectrum, the mean period of the intensity modulation is measured. This is realized by counting the number of extrema (i.e. measuring the rate at which the state of polarization changes as wavelength changes), in order to give a mean DGD. Alternatively, a Fourier transform into the time domain will also give a graph, and the RMS DGD value is determined from the standard deviation of the Gaussian curve (for fiber links with strong mode coupling).

Method B – Stokes Parameter Evaluation - Jones Matrix Eigenanalysis (JME)

Equipment

This method requires the following devices:
- A tunable narrowband source with three linear polarizers
- A polarimeter.



Principle

The three known states of polarized light enable the polarimeter to obtain the Jones matrix. The Jones matrix values at pairs of adjacent wavelengths provide the DGD value. The PMD is then calculated by simply averaging the obtained DGD values over the wavelengths.

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Method C – Interferometry: Traditional method (TINTY)

Equipment

This method requires the following devices:

- A broadband polarized source
- An interferometer (Mach-Zehnder or Michelson).

Principle

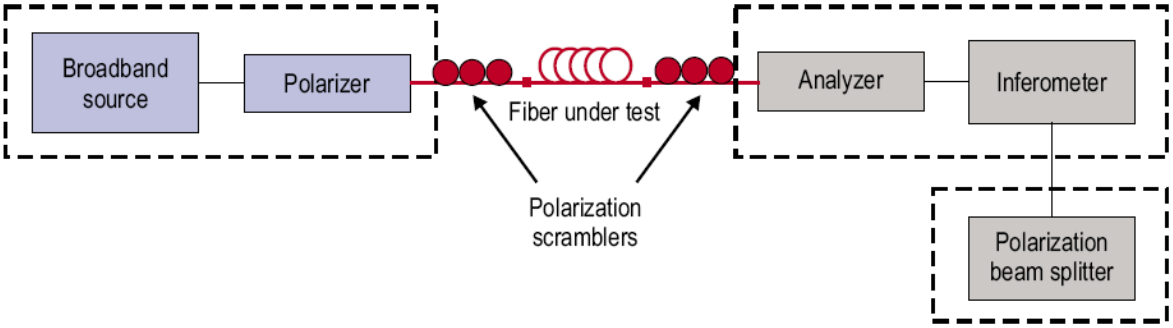
For fiber links (usually strong mode coupling), the result is an interferogram with random phases, and the mean DGD value is determined from the standard deviation of its curve. Nevertheless, the fringe envelopes obtained are a combination of two functions. An algorithm must be used to try to remove the central auto correlation peak which contains no PMD information.

Method D – Interferometry: Generalized method (GINTY)

Equipment

This method requires the following devices:

- A broadband polarized source
- An interferometer (Mach-Zehnder or Michelson) with a polarization beam splitter
- 2 polarization scramblers.



Principle

For fiber links (usually strong mode coupling), the result is an interferogram with random phases, and the mean DGD value is determined from the standard deviation of the curve. This time, the two signals of the polarization diversity detection allow to removing the contribution of the source auto-correlation peak. It is possible to obtain the interferogram without the central peak thanks to the polarization beam splitter. However the real benefit of this method is only obtained by the use of polarization scramblers, allowing to improve speed and absolute uncertainty of the measurement results.

Inter-comparison between methods

Inter-comparison results have been made by the international organizations, and at the present time, inter-laboratory measurements indicate that there is an agreement of +/-10% to +/-20% between all the different methods. This is well described in the TIA/EIA-455 PMD documents. There is fairly good statistical agreement between fixed analyzer and Jones Matrix Eigenanalysis. On the other hand, the interferometry and fixed analyzer with Fourier transform are having good statistical agreement. However there may have possible differences between the two types of methods.

The following measurements (DGD in ps) have been performed in the field, on different link configurations, with the same acquisition conditions.

New fiber measurements (on drums)

Distance	TINTY	FA	Difference
100 km	0.77 ps	0.85 ps	10%

New deployed fiber measurements (>2000)

Distance	TINTY	FA	Difference
69 km	0.282 ps	0.282 ps	1%
89 km	0.519 ps	0.479 ps	8%

Old fiber measurements (<1993)

Distance	TINTY	FA	Difference
16 km	7.26 ps	6.16 ps	16%
32 km	8.37 ps	7 ps	16%

This confirms the differences between Interferometric and Fixed Analyzer methods given by the TIA/EIA, in the region of 10 to 20%. Furthermore, measurements repeatability shows results variation, with both methods, due to the statistical changes of the PMD values.

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Advantages of the different test methods

Fixed analyzer	**JME**	**TINTY**	**GINTY**
Established in the market		Established in the market	
High dynamic range >45 dB (using hand held, rugged light source).	High dynamic range: up to 50 dB (using a benchtop light source)	High dynamic range: up to 65 dB (using a benchtop light source)	High dynamic range: up to 47 dB (using a benchtop light source)
Good absolute uncertainty	Good absolute uncertainty	Good absolute uncertainty but systematic error because of the interferogram central peak removal	Good absolute uncertainty
Min DGD measurement range suitable for any fibers	Min DGD measurement range suitable for any fibers	Min DGD measurement range suitable for any fibers	Min DGD measurement range suitable for any fibers
Possible to measure through multiple EDFA	Possible to measure through multiple EDFA		Possible to measure through multiple EDFA
Very fast measurement (from 5s)	Averaging not necessary but one acquisition required for each wavelength.		Very fast measurement (from 5s)
Robust and field dedicated instrument: no moving parts (Fabry-Perot filter technology) limiting risk of failure. Small and light.			
Very easy to use: No specific parameter settings necessary			
	Not sensitive to input polar-ization		Not sensitive to input polarization when using polarization scramblers
	Not sensitive to mode coupling		
	2nd order PMD measured directly		

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Disadvantages and limits of the different test methods

Fixed analyzer	JME	TINTY	GINTY
	High cost method for a field solution.		New interferometry method
	Laboratory solution, not field proven nor convenient (use of benchtop light source)	Not field convenient: Risk of failure due to moving parts.	Not field convenient: – Risk of failure due to moving parts. – Polarization scramblers required.
Averaging necessary but only over 30 dB total loss.		Long Measurement time. Averaging necessary	Limited dynamic range with portable light source
		Not easy to use: the correct DGD range must be set before testing.	
		Not possible to measure through EDFA	
2nd order PMD not measured directly but calculated		2nd order PMD not measured directly but calculated	2nd order PMD not measured directly but calculated
Max PMD limited to 60 ps suitable for any telecommunication fibers (1)	Max PMD limited to 50 ps suitable for any telecommunication fibers (1)		
Sensitive to input polarization		Sensitive to input polarization (2)	Sensitive to input polarization when no polarization scramblers in place

(1) Refer to chapter "when testing PMD"

Conclusion

There are no simple theoretical predictors of installed cable PMD, but PMD is more critical with older fibers that were manufactured with less geometrical control than today.

PMD remains the dominant bit rate-limiting effect in long single mode fibers, when chromatic dispersion is reduced by state-of-the-art techniques like compensated fibers or chirped gratings. PMD has to be measured in order to characterize the fiber dedicated to this transmission speed.

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