

# An Introduction to the Fundamentals of PMD in Fibers

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## Introduction: Importance of PMD for High Data Rate Transmission Systems

The continuous growth of Internet traffic is driving transmission system engineers to use higher and higher data rates in all segments of communication networks. Figure 1 illustrates the evolution of data rates over recent years for the most widespread transmission protocols. At the present moment 10 Gb/s SONET/SDH systems are most commonly deployed in long-haul networks but we are now at the advent of frequent 40 Gb/s deployments heralded by the recent announcements of the introduction of 40 Gb/s equipment to networks in Western Europe (Deutsche Telekom), the US (MCI) and Asia (CERNET). At the same time Ethernet and Fibre Channel (FC) transmission protocols that are used in Local Area Networks (LAN) and in Metropolitan Area Networks (MAN) have reached 10 Gb/s data rates.

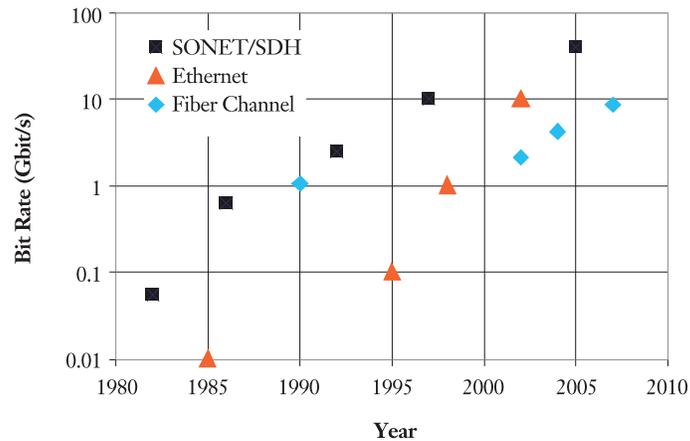


Figure 1. Data Rates for the Most Popular Transmission Protocols Have Risen Steadily Over the Last 20 Years

It is widely recognized that 40 Gb/s data transmission rates impose very strict requirements on the fiber plant and transmission systems deployed in the field. However, data rates of 10 Gb/s also impose similar significant performance requirements. In particular, Polarization Mode Dispersion (PMD) can be a serious limitation on certain fiber links operating at 10 Gb/s, particularly on links in older legacy networks. Recent papers written on the topic argue that even fibers made and deployed in the 1998-2001 time frame may be unusable for 10 Gb/s and higher data rate transmission, due to the challenges presented by PMD<sup>1</sup>. As network data rates continue to rise, it is becoming increasingly important to understand PMD and its potential impact on your network.

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The subject of PMD presents many challenges, including understanding the inconsistent terminology and the statistical nature of PMD and also comprehending the background to the advanced measurements techniques employed to calculate PMD. The purpose of this paper is to provide an introduction to the topic of PMD. This paper will explain the origin and nature of PMD, will clarify the terminology and statistical nature of PMD, and will examine the impact of PMD on high speed transmission systems.

### Basics of Fiber PMD

A telecommunication signal propagates in an optical fiber in the form of a modulated beam or wave of light (see Figure 2). Light is a form of electro-magnetic radiation which is characterized by having a particular wavelength and frequency. The wavelength is defined as the distance between the points in the electromagnetic wave where the electric field has highest amplitude (see Figure 3a). The frequency is defined as the number of complete wavelengths (or cycles) that traverse past a particular point in one second. The measure of frequency is Hertz (Hz), or cycles per second. The electromagnetic spectrum (see Figure 3b) consists of many different spectral regions defined by their respective wavelengths; for example the visible light that we are most accustomed to, ultra-violet light (UV) and the infra-red (IR) light that is actually used to transmit signals in fiber optic communications. In particular, IR wavelengths in the region of 1.55 microns ( $\mu\text{m}$ ) or 1550 nanometers (nm) are used to transmit optical signals over long distances in long-haul optical telecommunications networks, because optical fiber exhibits the lowest attenuation at this wavelength. All electromagnetic waves are characterized by polarization – the direction in which the electric field (E) of the wave is oscillating. For example in Figure 2 the electric field of the light wave oscillates in the direction of X-axis so one would call such a wave, X-polarized. Clearly, electromagnetic waves could have two polarizations – along the X axis or along the Y axis, and if the electric field E is not aligned with either axis, the electromagnetic wave would contain both polarizations.

The speed at which a light wave travels through an optical medium (denoted as  $v$ ) is dependent on the refractive index<sup>2</sup> of the medium typically denoted as  $n$ . The higher the refractive index the slower the speed of light and vice versa i.e.  $v=c/n$  where  $c$  is a speed of light in vacuum ( $c=3 \times 10^8$  meters/second (m/s)).

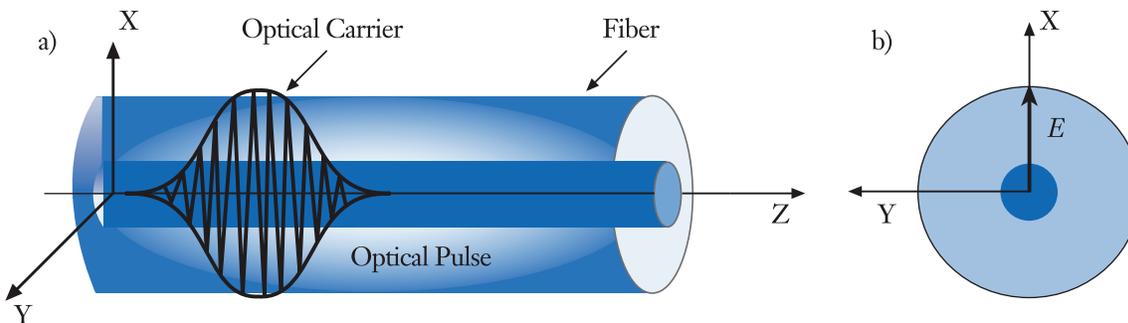


Figure 2. Modulated Beam

(a) Telecommunications signal is transported down an optical fiber in the form of a modulated beam or wave of optical light (optical carrier) (b) Light in an optical wave can have two polarizations (i.e. Two possible directions of electric field)

<sup>1</sup> “Polarization Mode Dispersion (PMD) Field Measurements: Audit of Newly Installed Fiber Plants” Sergio Barcelos, OFC/NFOEC 2005 paper NThC3.

<sup>2</sup> The value of the refractive index is dependant of the chemical and structural composition (e.g. diamond is carbon arranged in a particular crystal structure) of the material and is a measure of how light interacts with the chemical bonds within that material.

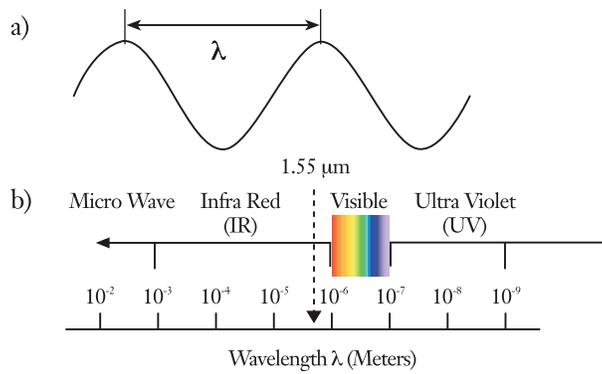


Figure 3. (a) Wavelength of the Electromagnetic Wave (b) The Wavelength Spectrum of Electromagnetic Radiation

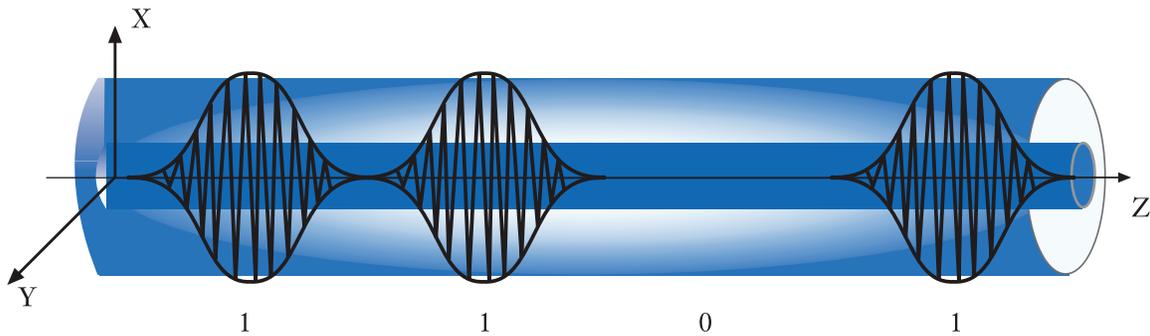


Figure 4. An Optical Wave which has been Modulated to Form the Data Code 1101  
*The diagram shows the optical carrier wavelengths encapsulated by the signal pulses.  
 The wave is polarized along the X-axis.*

A digital optical communications signal consists of an optical wave which is modulated into a series of “ones” and “zeros” in order to define the coded data. An optical communications signal is illustrated in Figure 4, where you can see that a “one” is represented by a light pulse, whereas a “zero” is represented by a time period of no light transmitted.

### Birefringence in Optical Fiber

Optical pulses propagate in an optical fiber with a speed determined by the fiber refractive index. In the case of an absolutely symmetrical optical fiber, the speed of light in the fiber should not depend on the polarization of the light (see Figure 5a) since light “sees” the same refractive indices independent of whether it is polarized along the X or Y axis. The refractive indices that define the speed of light for X or Y polarized light are denoted as  $n_x$  and  $n_y$  respectively. It is customary to draw a refractive index ellipse to illustrate graphically the refractive indices for light with a specific polarization<sup>3</sup>. The refractive index ellipse is an ellipse whose axes are proportional to the refractive indices  $n_x$  and  $n_y$ . Clearly, for the case of a fiber with an absolutely symmetric refractive index profile, the refractive index ellipse becomes a circle.

Now consider the case when the refractive indices in the X and Y directions are different and the refractive index ellipse indeed becomes an ellipse (see Figure 5b). This difference is called birefringence. Then the speed of light in the fiber becomes dependent on the wave polarization. In the example shown in Figure 5b, the refractive index  $n_x$  is higher than  $n_y$ , thus light polarized along the X axis propagates with a speed slower than that of the light polarized along the Y-axis. Typically the polarization that propagates with lower speed is called the “slow axis” whereas the polarization that propagates with the higher speed is called the “fast axis”.

<sup>3</sup> For more detailed definition of refractive index ellipse or in more general case index ellipsoid see Amnon Yariv “Optical Electronics”, published by Wiley; 3 edition, 1989, chapter 1.4.

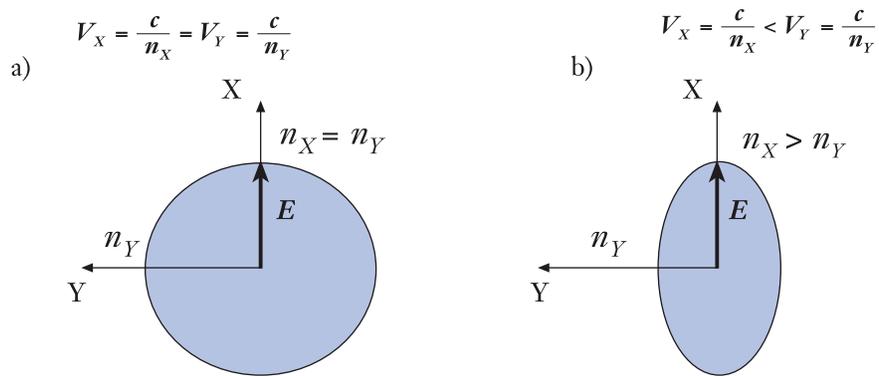


Figure 5. (a) Representation of a perfectly symmetrical fiber where the index ellipse is a circle and the speed of light does not depend on its polarization (b) Representation of the fiber with birefringence where X-Polarized light propagates slower than Y-Polarized light.  
 Here, the X and Y axes are called slow and fast axes, respectively.

Figure 6 shows how the birefringence of an optical fiber has the effect of slowing down the polarization state which is oscillating along the slow axis with the higher refractive index (the X-axis in Figure 5), relative to the polarization state oscillating along the Y axis. The net effect of this is that birefringence in the fiber introduces a delay between two polarization states. This delay is known as the differential group delay (DGD), and is usually denoted as  $\Delta\tau$  and is measured in picoseconds (ps) or 1 millionth of a millionth of a second ( $10^{-12}$  of a second).

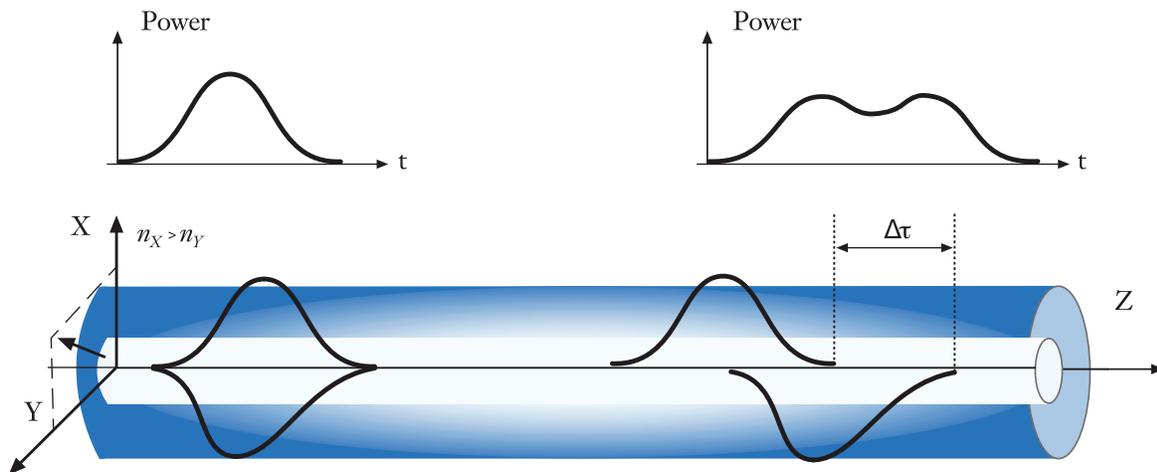


Figure 6. The Impact of the Birefringence on the Optical Pulse that has Two Equal Polarization Components  
 The birefringence in the optical fiber slows down the X-polarized state that sees the higher refractive index and causes a differential group delay (DGD) between the Polarization States, that results in pulse distortion often referred to as pulse splitting.

Typically, the situation depicted in Figure 6 occurs when the input optical pulse is polarized between the X and Y axis giving it a polarization component along both the X and Y axes (in our example in Figure 6 it is polarized at 45 degrees with respect to the X and Y axis). Since most telecom detectors are insensitive to the polarization of incident light, the difference in the propagation speeds of the X and Y components of the optical wave results in, and is detected as, a temporal broadening of the pulse at the detector. If the delay is large enough two distinct pulses arrive at the output of the birefringent fiber and this peculiar distortion is often referred to as “pulse splitting”. Such pulse distortion results in signal degradation and eventually in system outage.

## Sources of Birefringence

There are many ways in which a fiber can become birefringent (see Figure 7). Birefringence can arise due to an asymmetric fiber core or can be introduced through internal stresses during fiber manufacture, or through external stresses during cabling and installation. Optical fiber manufacturing processes are designed to yield fibers with a circular cross-section. Any deviation from this form will generally result in an elliptical core, which in turn will result in a refractive index difference between the X and Y axes of the elliptical core. Even if the fiber core is manufactured with an ideal circular cross-section its refractive index can be asymmetric across its cross-section due to stresses built into the fiber during the manufacturing process or stress that is externally applied during deployment or operation.

External asymmetric stresses can be introduced to the fiber during cabling and installation. Any non-uniform loading of the fiber cross-section, or bends or twists that are introduced to the fiber by sub-optimal cabling or installation will result in an asymmetric external stress being placed on the fiber.

An optical fiber will exhibit birefringence as a consequence of all of the above sources of internal and external stress.

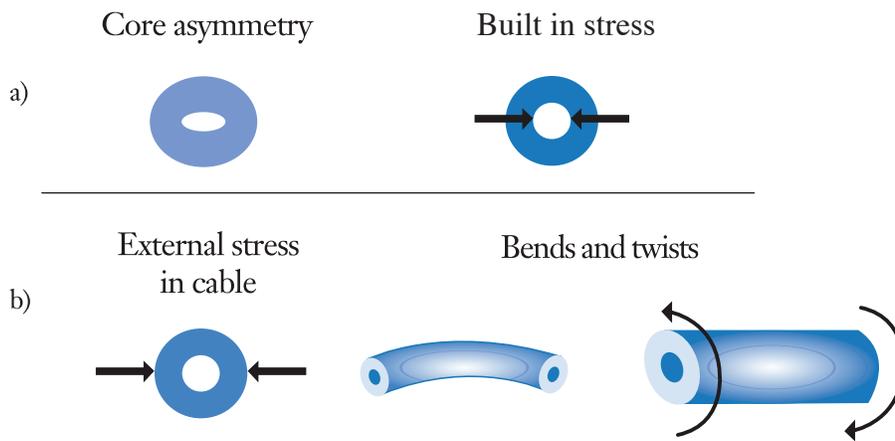


Figure 7. Sources of Birefringence

(a) Internal sources such as core asymmetry and built in stress (b) External sources such as bend twists and external stress applied to the fiber

## PMD is Not Just Birefringence

PMD is related to the differential group delay (DGD) caused by birefringence in optical fibers. However, the relationship between DGD and PMD is more complex due to the fact that fiber birefringence varies along its length, with different sections exhibiting different levels of birefringence both in terms of levels of refractive index asymmetry and the relative orientation of the slow and fast axis. Hence the fiber PMD can not be approximated to the PMD of one section of the fiber, and to investigate the nature of PMD we must represent the fiber as a series of concatenated birefringent sections of fiber separated by coupling sites, i.e. locations where the birefringence axes of one section are rotated with respect to the other (see Figure 8). The birefringent fiber sections are orientated randomly relative to each other. At each coupling site the relative alignment of the axes of the birefringent sections can drift with respect to each other with time due to variations in the environmental conditions (e.g. temperature or external perturbation of the fiber). As a result the overall instantaneous value of DGD exhibited by the concatenated series of birefringent sections changes randomly with time.

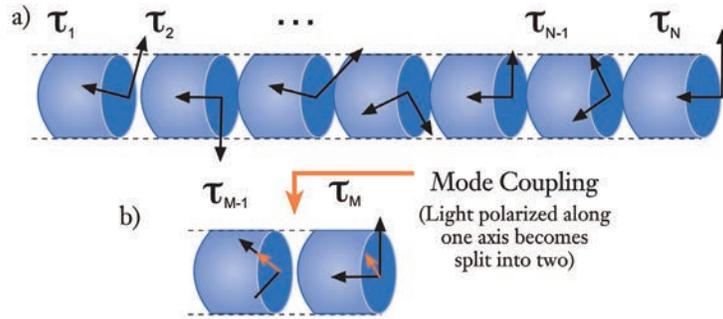


Figure 8. (a) Physical Model of Fiber PMD as a Concatenated Series of Birefringent Fibers with a Certain Length  
 (b) Separated by Mode Coupling Sites where the Birefringent Section is “Rotated” with Respect to the Adjacent Sections

If you were to measure the instantaneous value of DGD at the output of a fiber repetitively, you would observe that DGD is a random value. An example of a histogram of repetitive DGD measurements is shown in Figure 9. Numerous experiments and theory revealed that DGD histograms could be well approximated by a “Maxwellian” probability distribution (see histogram in Figure 9 and the curve corresponding to the Maxwellian distribution given by the formula above it). This distribution is controlled by only one parameter, the average DGD or  $\langle \Delta\tau \rangle$ . As shown in Figure 9 this average value is located slightly to the right of the probability density function’s maximum value. *The average value of DGD  $\langle \Delta\tau \rangle$  is known as the PMD of the fiber.*

$$PMD = \langle \Delta\tau \rangle \quad (1)$$

Many people use DGD and PMD terminology interchangeably<sup>4</sup>, which can be confusing, so it is important to note that PMD is a parameter that is the average of the DGD probability distribution<sup>5</sup>. However, let us also note that both DGD and PMD have the same units of time (usually measured in picoseconds).

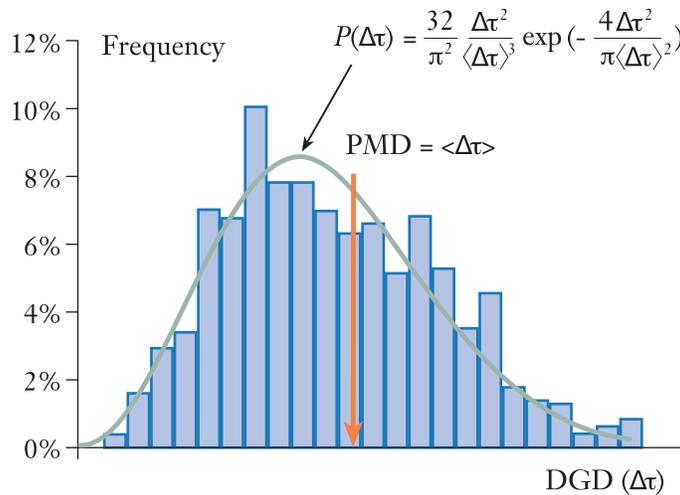


Figure 9. Distribution of DGD Measured in a Fiber with Birefringence

*The X-axis represents the instantaneous measured value of DGD and the Y-axis shows the frequency of the measured value. The distribution can be closely approximated using a Maxwellian Distribution as given by the formula above.*

<sup>4</sup> Sometimes DGD is referred to as “instantaneous PMD”. Another area of confusion comes from interchangeably using the term “PMD” as an experimentally measured parameter in the units of time and also as a name of the overall phenomenon apparently without reference to any physical units.

<sup>5</sup> The terminology accepted by the international standards body, International Telecommunication Union, ITU, is described in the Recommendation G.650.2. Corning Incorporated adheres to this use of terminology.

Numerous experiments with fibers of different lengths have revealed that the PMD of the fiber is proportional to the square root of the fiber length (L) multiplied by a proportionality coefficient. This coefficient is called the PMD coefficient ( $PMD_{Coeff}$ ) and is typically measured in units of picoseconds per square root kilometer ( $ps/km^{1/2}$ ).

$$PMD = \langle \Delta\tau \rangle PMD_{Coeff} \sqrt{L} \tag{2}$$

The PMD coefficient is the parameter that is typically specified for commercially available fiber. The PMD coefficient represents the PMD characteristics of one particular length of fiber. In a fiber link consisting of several successive concatenated lengths of fiber, each length will have a different actual PMD coefficient. Very often the PMD coefficient is referred to as “PMD” which also adds to the confusion regarding the terminology.

### The Impact of PMD on System Performance

PMD (average DGD) increases with transmission distance, thus as the distance increases one is more likely to observe large DGD at the receiver. The impact of DGD will manifest at the receiver in the form of signal distortion (see for example Figure 6). The distortion arises when the time slot (or a bit period,  $T_B$ ) of an individual pulse is stretched by the PMD induced delay to the point where the tail-end of a leading pulse overlaps with the leading edge of a subsequent pulse. This is called Inter-Symbol Interference (ISI), as shown in Figure 10. The stretching of the pulse also reduces the extinction ratio (the difference in amplitude between the upper level, representing a “1”, and the lower level, representing a “0”, of the signal) and introduces a system penalty since the receiver may not always be able to decide whether it sees a “1” or a “0”.

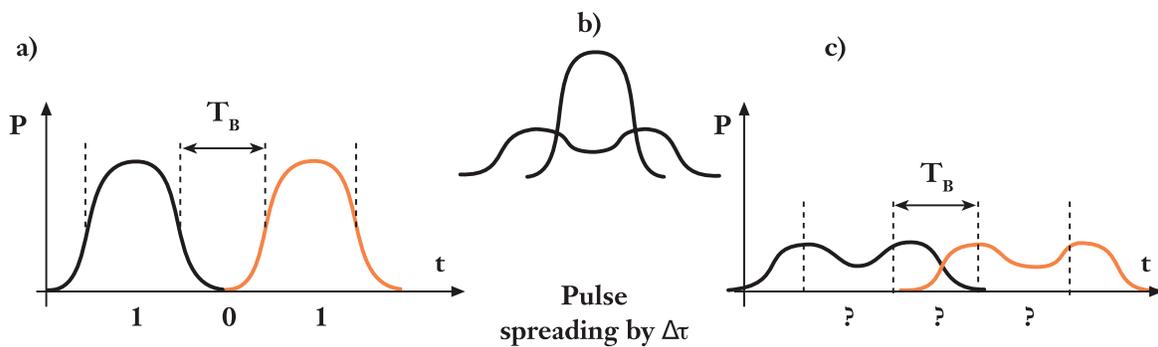


Figure 10. Formation of Inter-symbol Interference Due to PMD

(a) The shape of the original pulse sequence where each pulse occupies a designated bit slot (b) Spreading of the pulse due to DGD (c) Shape of the overlapped pulses at the receiver where individual pulses have “leaked” out of their designed bit slots making it difficult for the receiver to decide whether it sees “1” or “0”.

### System Penalty

System impairment is often quoted in relation to power penalties. If a system suffers a 1 dB power penalty this implies that there exists a source of distortion in the system that causes degradation in the system performance equivalent to reducing the received signal power by 1 dB. The other way to interpret power penalty (e.g. 1 dB) is to say that the negative impact of distortion on the system can be compensated by increasing the power launched at the transmitter by 1 dB.

It is intuitively clear that higher DGD will cause a higher penalty and vice versa. A typical power penalty curve is shown in Figure 11<sup>6</sup>. One can see that a 1 dB power penalty is incurred when the DGD reaches 30% of the bit period.

<sup>6</sup> ITU-T Recommendation G.691 (2003), page 29.

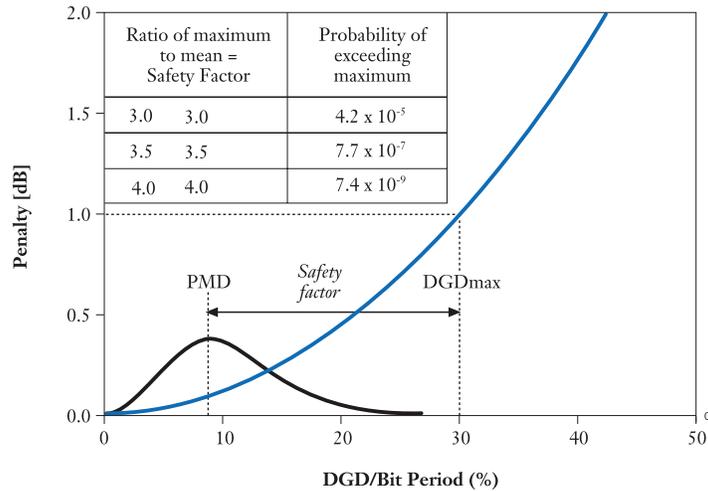


Figure 11. PMD Significance on System

*PMS has a significant impact on system performance when the DGD ( $\Delta\tau$ ) exceeds ~30% of  $T_B$ .*

System designers will normally allow for a certain level of system penalty due to PMD, and this maximum system penalty will have an associated maximum DGD value (DGDmax). In an optical fiber exhibiting PMD, the random nature of the orientation of the coupling sites between birefringent sections within the fiber length results in a fluctuating DGD. The system penalty associated with PMD in an optical fiber is dependent on the DGD and so as the instantaneous DGD varies randomly with time, so too does the system penalty. The blue curve in Figure 11 shows the probability distribution of the DGD. Because of the random nature of DGD, in principle, any, even large values of instantaneous DGD can occur including those that exceed the maximum DGD value associated with the pre-selected desired maximum value of power penalty, i.e. DGDmax. The probability of this event though is small and is determined by how low the average of the DGD distribution, i.e. the PMD, is with respect to DGDmax. The ratio between DGDmax and the PMD is referred to as the safety factor. It is intuitively clear that if a designer desires to reduce the probability of the DGD of the link reaching DGDmax, then he must increase the safety factor. ITU Recommendations<sup>7</sup> provide reference tables with those factors. The inset in Figure 11 illustrates these factors, and shows that if a designer wants to ensure that the probability of the DGD of a fiber link exceeding DGDmax is less than  $4.2 \times 10^{-5}$ , then he must design the link with a PMD that is 1/3 of DGDmax, with the DGDmax being, in turn, only 30% of the bit period. This yields the mnemonic rule often used to determine the maximum allowable PMD of the link:

$$PMD < 0.3 \times \frac{1}{3} T_B = \frac{1}{10} T_B \quad (3)$$

### PMD in Standards

ITU Recommendations provide standards requirements for the equipment manufacturers in order to enable multivendor compatibility. For this purpose, standards bodies try to “compartmentalize” the transmission systems into sections such as the transmission medium, the interfaces (transmitter receiver), the amplifiers, etc. In such an approach the transmission medium, i.e. the optical fiber deployed in a cable, must satisfy certain requirements. For example, the fiber section between optical amplifiers (span) should have a certain loss, dispersion, return loss, etc. On the other hand, requirements for interfaces are written with the assumption that optical signal distortion does not exceed a certain level. For example, from an interface perspective, ITU standards (see for example G.691, G.657) treat the whole optical path i.e. fiber, optical components, amplifiers, etc. as a “black box” (see Figure 12). In the treatment of PMD of such a system it is required that the DGD exhibited by this “black box” should not exceed the DGDmax, that is defined as 30% of the bit period i.e. 30 ps for a 10 Gb/s signal. Using that requirement and knowing the required level of probability of exceeding this DGDmax, the PMD allowable for both the components and the fiber can be calculated. These calculations are fairly involved and fall beyond the scope of this paper; however in one simplified case we can easily calculate fiber length using equation 3.

<sup>7</sup> See for example ITU-T Recommendation G.691 (2003), page 12.



Figure 12. From Interface Point of View All Optical Path is Black Box with DGD Below Some Maximum Allowed Level DGDmax

If the only contribution to PMD comes from the optical fiber (meaning that (unrealistically) the PMD of all other optical components are zero) and the fibers used for constructing the link have identical PMD coefficients then the requirements for fiber PMD could be calculated simply from Equation (3). In constructing Table 1 we have used Equation 3 to determine the allowable PMD for various data rates and have used Equation 2 to calculate the associated fiber length limitations for fibers with PMD coefficients of  $0.02 \text{ ps/km}^{1/2}$  and  $1 \text{ ps/km}^{1/2}$  (representative of contemporary and older fiber vintages) under these idealistic conditions.

Due to the non-zero PMD contributions from the other optical components and due to the fact that fibers used in cable manufacturing have different PMD coefficients, PMD requirements for fiber are expressed in terms of  $\text{PMD}_Q$  in ITU Standards (see recommendations G.652, G.653, G.654, G.655 and G.656). The meaning of  $\text{PMD}_Q$  and rationale for using it are discussed in Appendix 1.  $\text{PMD}_Q$  is the industry recognized convention for specifying fiber and cable PMD.

Data Rate (Gb/s)	$T_B$ (ps)	PMS (ps)	L (km) ( $\text{PMD}_{\text{coeff}} = 0.02 \text{ ps/km}^{1/2}$ )	L (km) ( $\text{PMD}_{\text{coeff}} = 1 \text{ ps/km}^{1/2}$ )
2.5	400	40	$4 \times 10^6$	1600
10	100	10	$2.5 \times 10^5$	100
40	25	2.5	16,000	6.25

Table 1. Table Summarizing Allowable PMD for Different Data Rates and Transmission Distance for Fibers with PMD Coefficients of  $0.02 \text{ ps/km}^{1/2}$  and  $1 \text{ ps/km}^{1/2}$  Respectively

### Conclusion

PMD can be a severe system impairment, particularly in older, vintage fiber which has high levels of PMD or in extended systems that have increased PMD due to longer fiber reaches and a larger number of optical components.

As data rates continue to rise, PMD is becoming a far more prevalent issue. At low data rates, like 2.5 Gb/s, the bit period is long relative to the accrued delay (even over the longest systems) and pulse distortion does not occur. However, as systems move to higher data rates like 40 Gb/s the bit period is drastically shortened, and PMD becomes a very significant issue. Consequently, the need for understanding of PMD and its implications has risen in prominence and importance.

In this paper we have explored the basics of fiber PMD and have shown that fiber PMD is a parameter which is related to the DGD that is introduced due to birefringence in optical fiber. We have considered the treatment and impact of PMD in an optical system and have discussed the techniques used in system design to build in system penalty allowances for impairments due to PMD.

## Appendix. Concept of Link Design Value ( $PMD_Q$ )

In this section we will discuss the PMD related specifications given in the International Telecommunication Union (ITU) standards (generally referred to as ITU recommendations). For example, if the reader opens any of the five current recommendations that describe current single mode fiber products that are used in long haul networks (recommendations G.652 - G.656) they will see the specification for  $PMD_Q$  on the last line of the table for fiber and cable attributes, as illustrated in Figure 13 (the actual value of  $PMD_Q$  will vary depending on the recommendation).

PMD Coefficient	M	20 Cables
	Q	0.01%
	Maximum $PMD_Q$	0.5 ps/ $\sqrt{\text{km}}$

Figure 13 . Section of the Table with Fiber and Cable Attributes that shows the PMD Related Specification in the G.652 Recommendation (2005 Edition)

But what are the meanings of M, Q and  $PMD_Q$ ? Why can the recommendation not specify “just PMD”? The intent of this Appendix is to give answers to these questions at a relatively high level (avoiding rather complicated mathematics).

In order to understand the meaning of the parameters M and Q we need to remind the reader how cable is made and deployed in terrestrial long-haul networks. Typically, a cable manufacturer would acquire a set of fibers on many individual reels from a fiber manufacturer, would then color the fibers and then process them into a cable. As optical cable manufacturing is typically a very cost sensitive process, even if fiber attributes are available for each individual fiber reel (i.e. a range of measured fiber attributes are supplied with each fiber reel ID), they are not tracked after the cable is made.

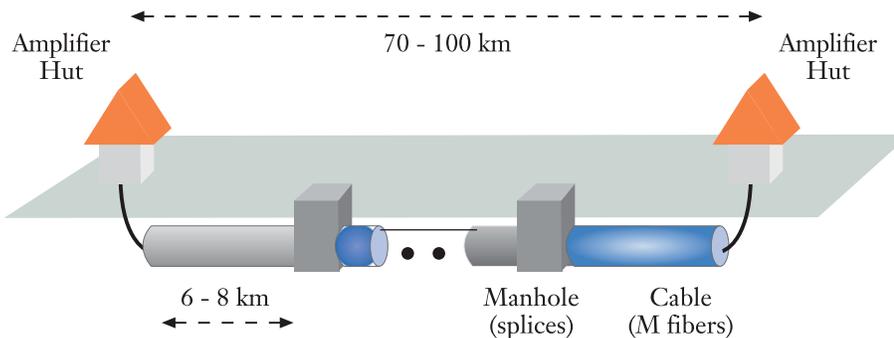


Figure 14. Schematic of a Typical Deployment of Optical Cable in a Terrestrial Network

After the cable is made, it is cut into shorter lengths of 6-8 km in order to facilitate its deployment either in an installed duct or using direct burial. These shorter sections of optical cable are then connected to each other (fibers of the same color are spliced and placed in the protective splice enclosures) to form an optical link. Thus, the overall link is made up from a number of fiber pieces whose PMD coefficients are arbitrarily drawn from cabler inventory and for practical purposes should be considered as random.<sup>8</sup> This randomness in the PMD coefficients of the constituent fibers, and the fact that the fiber optic link is made up of a number of fibers, drives the need for the statistical characterization of link PMD that is embodied in the concept of the PMD link design value, which is also known as  $PMD_Q$ .

<sup>8</sup> We need to point out here one of the major widespread confusing issues. The PMD coefficient is an average of observed random DGDs at the output of the fiber. By itself, for a given fiber, the PMD coefficient is NOT a random number, in the same way as an average is not a random number, but it is a characteristic of the random distribution of DGDs. However, in the cable, the PMD coefficient is treated as a random number because the fiber sections making up the cable are drawn randomly from the fiber distribution in the cable manufacturer inventory and consequently the information about the PMD coefficients of the individual fiber sections is lost. Thus, the PMD coefficient in  $PMD_Q$  calculations is not “fundamentally” random but is considered random due to logistical manufacturing reasons. The confusion comes from incorrect interchangeable use of PMD and DGD terms and from the notion that randomness of the PMD coefficients in the cable originates from the randomness of DGDs.

For the statistical definition of  $PMD_Q$  an imaginary reference link consisting of  $M$  equal length fiber sections is considered. Each section of the link has its own PMD coefficient value that is drawn from the PMD coefficients of the fibers produced by the fiber manufacturer. Assuming that you know the PMD coefficient of each individual fiber section, then the PMD of the link can be calculated using the formula from the bottom of Figure 15.

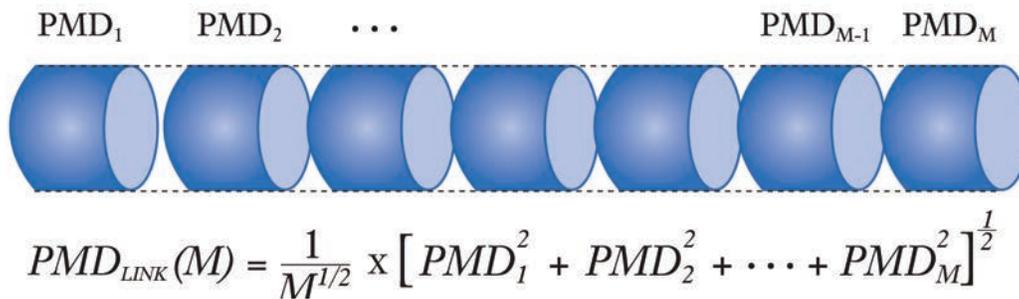


Figure 15. Schematic of the Reference Link Made with  $M$  Fiber Sections of the Same Length and the Formula to Calculate PMD Coefficient of the Link

It is clear that since the process of selecting fibers from the fiber inventory supplied by the fiber manufacturer is random, the link PMD coefficient is by itself a random value. Qualitatively, if a fiber maker produces fibers with large PMD coefficients it is more likely that the link PMD will be high and vice versa. So the quality of the distribution of PMD coefficients may be controlled, for instance, by requiring that probability of the link PMD coefficient being higher than a certain threshold number must be very small. In particular, in the ITU recommendations G.652-G.656 the number of fiber sections in the reference link is chosen to be 20 and is designated by letter  $M$  i.e.  $M=20$ . The threshold value that that link PMD coefficient shall not exceed in most of cases, is designated as  $PMD_Q$ . The probability of exceeding this threshold value  $PMD_Q$  is denoted as  $Q$  and is always chosen to be appreciably small e.g. in G.652-656 recommendations  $Q=10^{-4}$  or 0.01%. This  $PMD_Q$  value can be used to calculate the PMD contribution of the fiber, that can be used together with the PMD contribution from other components (e.g. demultiplexer) and subsystems (e.g. optical amplifier) to calculate the overall PMD of the link.

So what is the meaning of the specification shown in Figure 13? It means the following: fibers made by manufacturer  $X$  are compliant with this recommendation if the probability of the PMD coefficient of the link, made with  $M=20$  cable sections of the same length, exceeding the value of  $PMD_Q=0.5 \text{ ps/km}^{1/2}$  is less than  $Q=0.01\%$ . But how would the buyer of such fiber interpret the probability clause? One way to interpret the probability clause is to imagine that the buyer would buy, let's say, 1,000,000 links of such cabled fiber and after measuring the PMD coefficient of each of the links, the buyer finds that  $N$  links have PMD coefficients higher than  $PMD_Q=0.5 \text{ ps/km}^{1/2}$ . If  $N/1,000,000 < 10^{-4}$  i.e.  $N < 100$  then fibers from manufacturer  $X$  are compliant with the aforementioned recommendation, however, if  $N > 100$  then the buyer can claim that the  $PMD_Q$  specification is violated.

Specifications based on probability functions are confusing to some people but they do exist even for some consumer products when the product contains a desired attribute only with a certain probability. For example a lottery ticket has only a finite probability to be a winning ticket and this probability in many cases is stated explicitly by the rules of the lottery. How is this probability enforced by the lottery issuer? In most cases they show the act of drawing and advertise the fact that the number of possibilities e.g. combination of numbers on the ticket, is finite.

Another, more complex, example, but somewhat more relevant to the concept of  $PMD_Q$ , is the side effects associated with some drugs. Assume that drug  $Z$  develops a side effect in some people after taking it for  $M$  consecutive days. The drug manufacturer in his disclosure states that this side effect will affect less than  $Q$  percent of all patients taking this drug. In this example the analogy for  $M$  and  $Q$  parameters are fairly evident but what would be the parameter analogous to  $PMD_Q$ ? Well, most likely it will be "suffering" of the patient but pharmaceutical companies would probably prefer not to quantify it as that!

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