Reference Guide to Fiber Optic Testing

Volume 2

JDSU

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Advanced Fiber Optic Testing

High-Speed Fiber Link and Network Characterization

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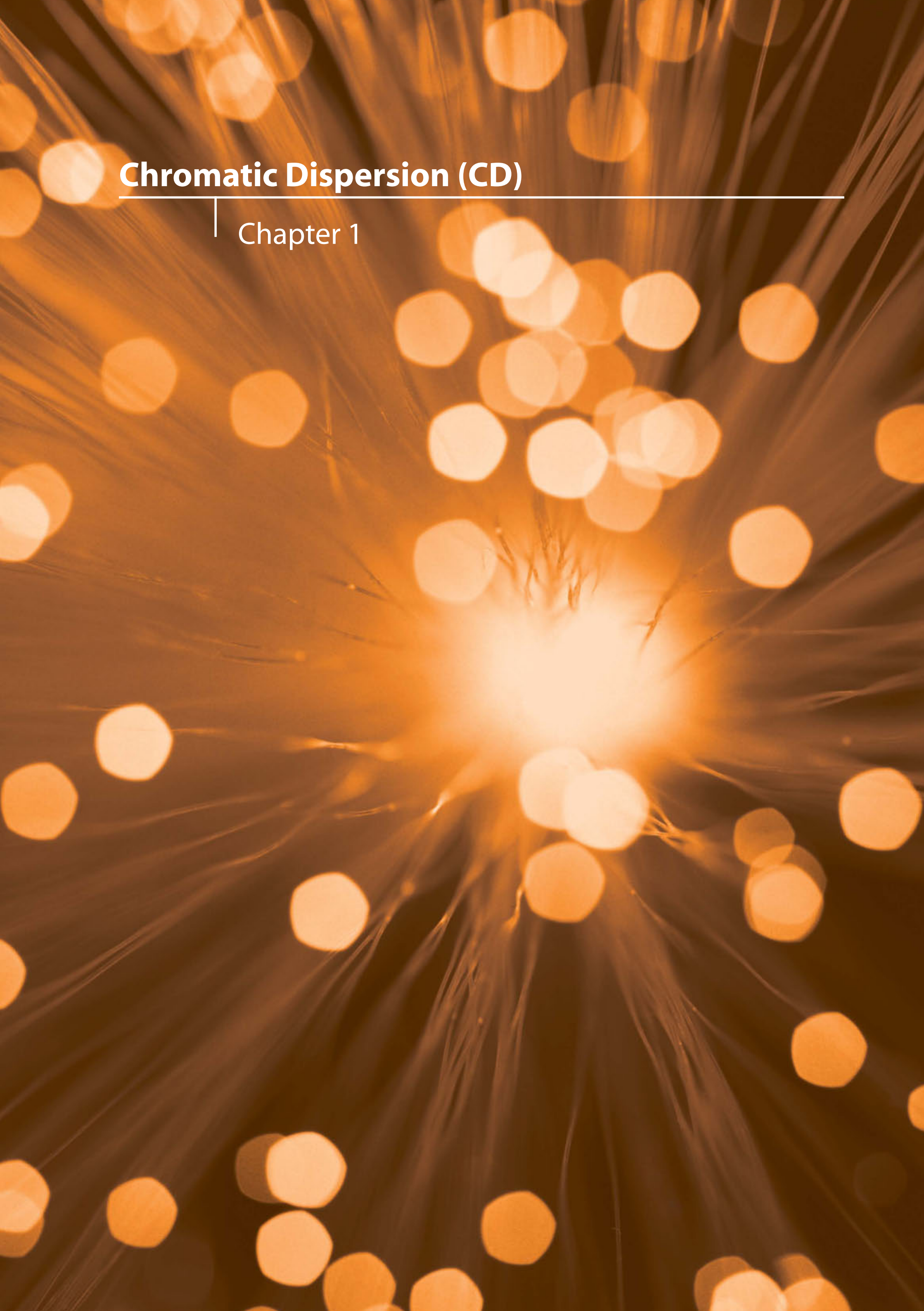
Table of Contents

Preface

A steadily increasing demand for transmission capacity forces service providers to upgrade their networks periodically to higher data rates or a higher number of wavelengths in dense wavelength division multiplexing (DWDM) systems. However, before such upgrades can be made, operators must verify that the deployed fiber infrastructure meets certain performance and reliability requirements. In addition to conventional loss and continuity testing, three main parameters must be considered for such upgrades: the chromatic dispersion, polarization mode dispersion, and the attenuation profile of the fiber. This volume addresses these parameters as well as associated methods for measuring each.

Chromatic Dispersion (CD)

Chapter 1



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Chromatic Dispersion (CD), an important fiber parameter, limits transmission capacity when bit rates increase, especially with optically amplified medium-to-long links. Characterizing the CD of the fiber is critical toward understanding the transmission limitations and implementing the right compensation solution to comply with transmission system requirements. Various methods can be used to measure CD.

1.1 Definition of Chromatic Dispersion

CD is the property of a medium (optical fiber) that makes different light wavelengths propagate at different speeds as they travel in it. In an optical fiber, both the wavelength dependence of the material itself (glass) and the properties of the structure of the index of refraction (IOR) create the guide in which the light is confined and propagating.

In optical telecommunications transmission, a pulse of light made up of multiple wavelengths (colors) that are each traveling at different speeds (group velocities), because of CD. The pulse spreads as wavelengths arrive at differing intervals. The wavelength dependence of the group velocity is formally known as group velocity dispersion. However, the terms group velocity dispersion and CD are typically used interchangeably in describing the propagation of wavelengths at different speeds.

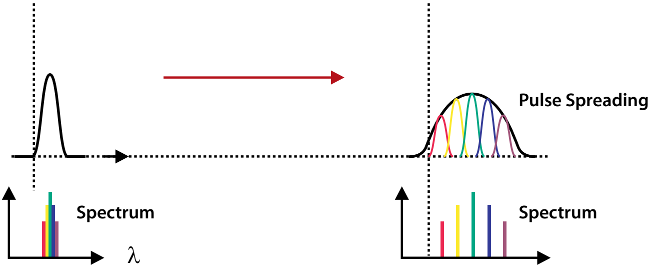


Figure 1: Pulse spreading caused by wavelengths traveling at different group velocities

Pulse spreading in dense wavelength division multiplexing (DWDM) optical transmissions can extend into adjacent bit periods and impair or reduce transmission quality, thus resulting in poor signal reception. Therefore, characterization of the CD is vital toward ensuring signal transmission quality.

CD is the dominant dispersion mechanism in single-mode fibers.

1.2 Chromatic Dispersion

1.2.1 Chromatic Dispersion Parameters

The CD of a given fiber represents the relative arrival delay (in ps) of two wavelength components separated by one nanometer (nm). Consider these four parameters:

- CD value of a given wavelength—expressed in ps/nm (CD may change as a function of wavelength)
- CD coefficient (referred as D)—the value is normalized to the distance of typically one kilometer expressed in ps/(nm x km)
- CD slope (S)—represents the amount of CD change as a function of wavelength expressed in ps/nm²
- CD slope coefficient—the value is normalized to the distance of typically one kilometer expressed in ps/(nm² x km).

The zero dispersion wavelength, λ_0, expressed in nm, is defined as a wavelength with a CD equal to zero. Operating at this wavelength does not exhibit CD but typically presents issues arising from the optical nonlinearity and the four-wave mixing effect in DWDM systems. The slope at this wavelength is defined as the zero dispersion slope (S_0).

1.2.2 Chromatic Dispersion Variation

CD usually does not vary significantly with time and installation conditions because of its low sensitivity to temperature, typically –00.0025 ps/(nm x km x °C) for the coefficient and 0.0025 ps/(nm² x km x °C) for the slope.

1.2.3 Negative and Positive Chromatic Dispersion

Short wavelengths travel faster than long ones when CD is positive. When CD is negative, short wavelengths travel slower. The opposite is true for long wavelengths, which travel slower when CD is positive and faster when CD is negative.

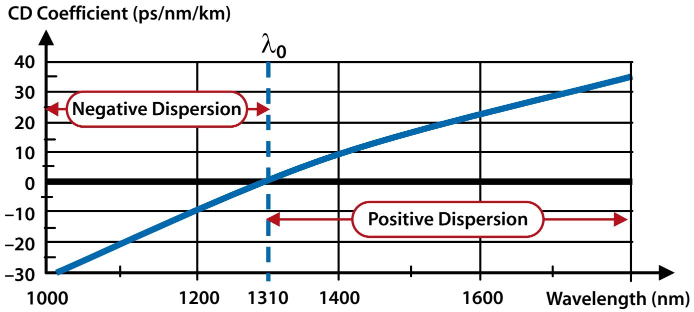


Figure 2: Negative and positive CD

Negative dispersion is frequently used to compensate for excessive positive dispersion in a fiber transmission network.

1.2.4 Dispersion Slope

The dispersion slope (S) describes the amount of change in CD as a function of wavelength.

- expressed in units of ps/(nm^2 x km)
- slope at λ_0 shown as S_0 and expressed in ps/(nm^2 x km)

As shown below, the CD is the derivative of the relative pulse delay. The CD slope is the derivative of the CD values.

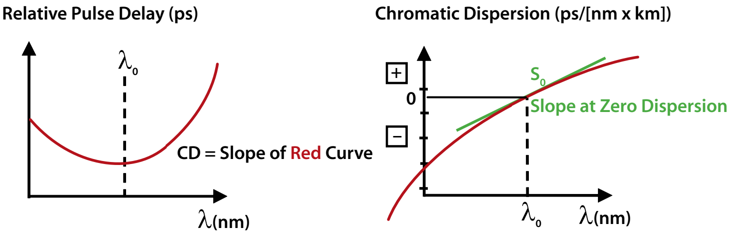


Figure 3: Example of pulse delay, CD, and dispersion slope

Fiber manufacturers use the dispersion coefficient (ps/[nm x km]) to specify the parameters for fiber, whereas equipment manufacturers use the total dispersion value (ps/nm) to ensure the adequacy of fiber for transmitting given wavelengths at given bit rates.

Table 1: Example of optical fiber CD coefficient specifications

C-Band: 1530 to 1565 nm	2.6 to 6.0 ps/(nm x km)
L-Band: 1565 to 1625 nm	4.0 to 8.9 ps/(nm x km)
Dispersion slope at 1550 nm	≤0.05ps/(nm² x km)

Lower dispersion slopes result in fewer dispersion changes throughout the wavelength and thus CD remains constant as a function of wavelength. For high-speed, multichannel DWDM networks, lower dispersion slopes enable more uniform, optimal performance across the DWDM wavelength.

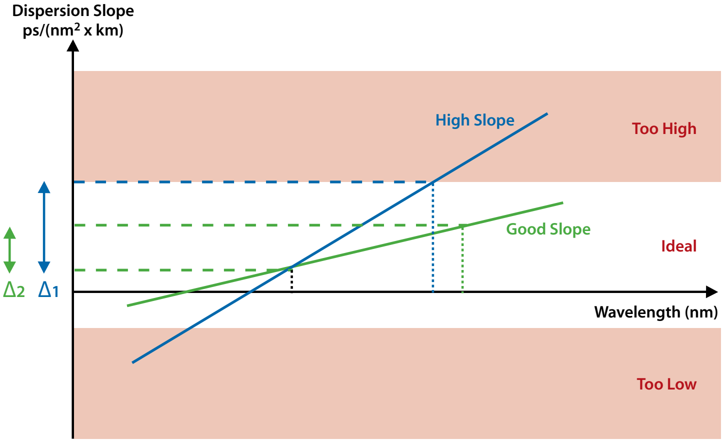


Figure 4: Dispersion slope variation

Dispersion compensation modules offset both the fiber dispersion as well as the dispersion slope thus balancing CD across the full DWDM wavelength. This capability is critical for Reconfigurable Optical Add/Drop Module (ROADM)-enabled networks as necessary broadband dispersion compensation is typically inserted at each ROADM node.

1.3 Causes of Chromatic Dispersion

Material and waveguide dispersion combine to cause CD in single-mode fibers.

1.3.1 Material Dispersion

The IOR for the material that makes up the fiber core, such as glass or/and dopants, depends upon wavelength. Consequently, the speed (group velocity) of each wavelength component can vary with wavelength.

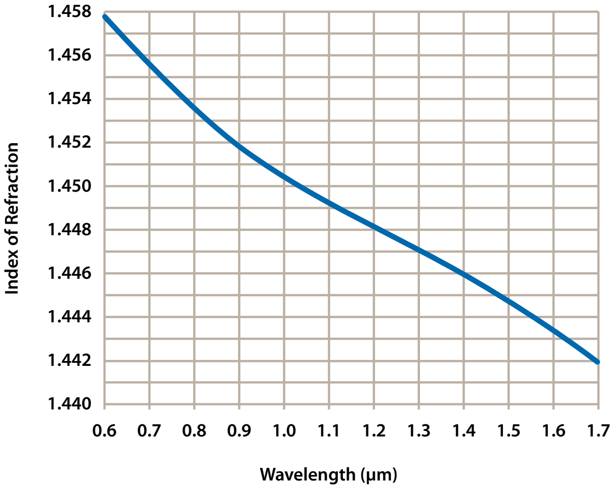


Figure 5: Refractive index of silica glass used in optical fiber as a function of wavelength

1.3.2 Waveguide Dispersion

Waveguide dispersion is the variation in group velocity of different wavelength components of light caused primarily by the mode field diameter (MFD), or the diameter of the light beam within the wavelength of a single-mode fiber.

Engineering differences in the IOR between the fiber core and cladding regions cause light to propagate faster in the cladding than in the core. The propagation velocity difference is largely independent of wavelength. Therefore, as the MFD increases, a greater percentage of the light propagates within the cladding region resulting in a faster propagation.

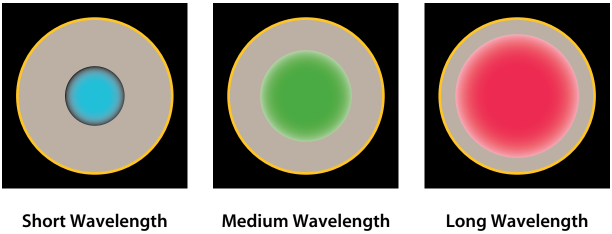


Figure 6: Variation of the MFD according to the wavelength

Longer wavelengths exhibit larger MFD and, therefore, faster propagation.

The fiber index profile (variation of the IOR in the fiber) and the MFD (light surface of the wavelength) together define the waveguide dispersion.

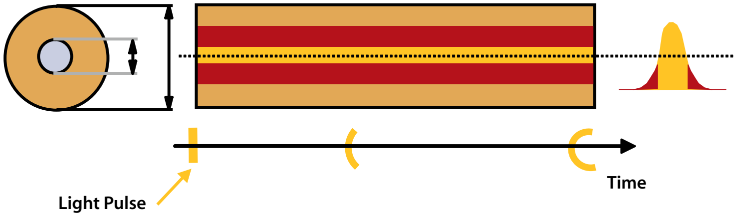


Figure 7: Light propagates faster in the cladding (red) than in the core (orange)

The waveguide dispersion (per unit length) depends on many parameters:

- Δn, the difference between the core IOR and the cladding IOR, or index profile
- core diameter—as core diameter decreases, dispersion generally increases
- fabrication of the fiber (determines core and cladding shape as well as radial index profile).

Fiber manufacturers typically adjust the waveguide dispersion to achieve certain CD characteristics.

1.3.3 Combined Chromatic Dispersion

Combined CD refers to the value for both material and waveguide dispersions together. The total combined CD for a fiber link depends on distance (km).

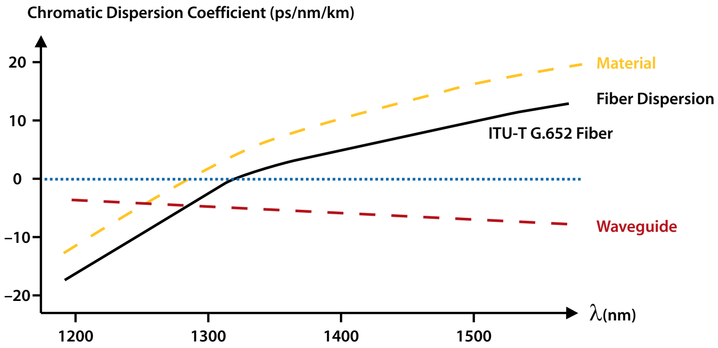


Figure 8: Total CD of a single-mode fiber = material + waveguide dispersion

Further discussions of CD and its measurements refer to combined CD, both the material and waveguide dispersions.

1.4 Fiber Types—The CD History

Fiber manufacturers continue to manipulate CD to produce different types of fibers for different applications and requirements. The International Telecommunication Union (ITU) has classified these various single-mode fibers into four main categories according to their CD properties: Non-Dispersion-Shifted Fiber (NDSF), Dispersion-Shifted Fiber (DSF), Non-Zero Dispersion-Shifted Fiber (NZ-DSF), and Wideband NZ-DSF.

Note: CD is not limited to single-mode fibers but also impacts multimode fibers. Multimode fibers are not considered in this document.

1.4.1 Non-Dispersion-Shifted Fiber

ITU-T G.652 fiber, often referred to as standard single-mode fiber (SSMF), was the first type of single-mode fiber manufactured. It was originally developed for optimized transmission around 1310 nm, with an abrupt index profile change between the core and the cladding (see figure below). Today, the SSMF is well suited for DWDM transmission in the C and L bands.

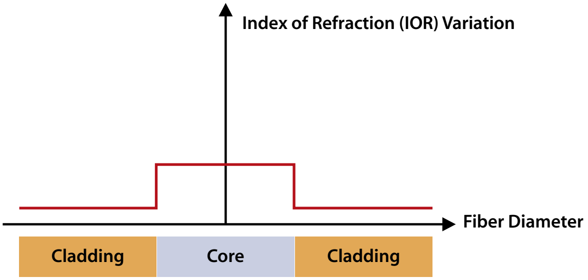


Figure 9: Schematic of index of refraction variation for an SSMF

1.4.2 Dispersion-Shifted Fiber

Dispersion-shifted fibers were designed with the zero dispersion wavelength moved within the 1550 nm region to increase the reach of long-distance transmission systems as well as to take advantage of the lower fiber attenuation. Classified as ITU-T G.653 fiber, it is ideal for single wavelength transmission in very long haul networks.

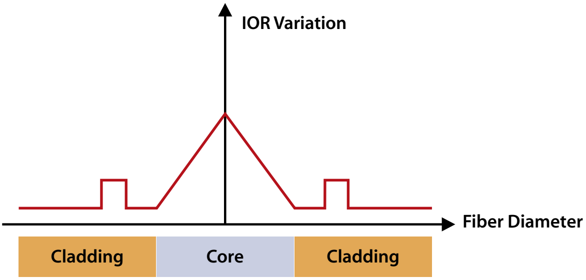


Figure 10: Schematic of index of refraction variation for a DSF

1.4.3 Non-Zero Dispersion-Shifted Fiber

With the advent of DWDM applications, a slightly positive or negative CD is desirable for wavelengths around 1550 nm as it eliminates nonlinear interactions between multiple DWDM channels, known as four-wave mixing. Typically, fiber classified as ITU-T G.655 has a CD magnitude one-third that of NDSF of positive or negative dispersion.

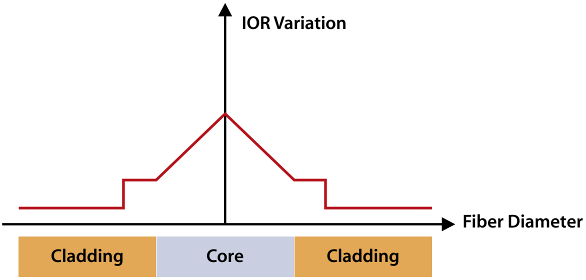


Figure 11: Schematic of index of refraction variation for an NZ-DSF

1.4.4 Wideband NZ-DSF

A newly standardized fiber type known as ITU-T G.656 offers a wider WDM transmission capability that extends beyond the conventionally defined C- and L-bands (nominally 1530 to1565 nm and 1570 to1610 nm, respectively). It offers a moderate dispersion (2 to 14 ps/[nm x km]) between 1460 and 1625 nm wavelengths.

1.4.5 Graphical Summary

Each of the fiber types described has its own dispersion properties. The amount of dispersion versus wavelength and the dispersion slope and the zero dispersion wavelength vary according to the fiber type. Also, note that each fiber type and the specified dispersion properties provide a range of acceptable values and, therefore, actual dispersion properties may vary from one fiber segment to the next.

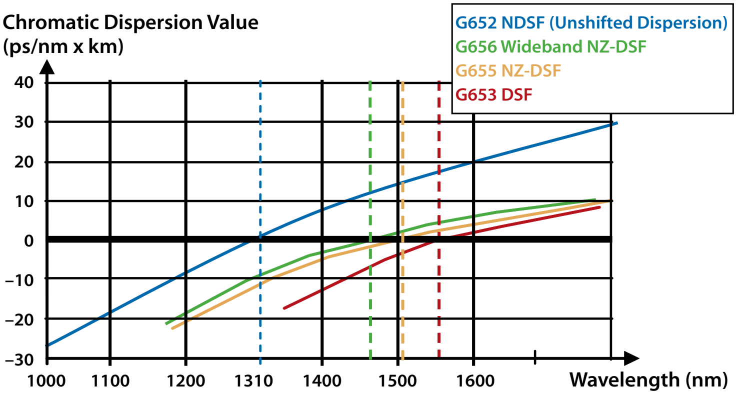


Figure 12: Dispersion curves according to fiber types

1.4.6 ITU-T Technical Specifications

As mentioned earlier, the ITU differentiates each fiber type and provides requirements on relevant technical parameters such as the zero dispersion wavelength (λ_0), the dispersion slope (S_0) at λ_0, the dispersion coefficient (D_{1550}) at the wavelength of 1550 nm, and the dispersion slope at 1550 nm. The following tables provide relevant requirements for each class of general fiber type (some fiber types have subtypes, such as G.652.A and G.652.B).

Table 2: ITU-T G.652 CD specifications

λ_{0min}	1300 nm
λ_{0max}	1324 nm
S_{0max}	0.092 ps/(nm^2 x km)
D_{1550} (typical value)	17 ps/(nm x km)
S_{1550} (typical value)	0.056 ps/(nm^2 x km)

Table 3: ITU-T G.653.A CD specifications

λ_{0min}	1500 nm
λ_{0max}	1600 nm
S_{0max}	0.085 ps/(nm^2 x km)
λ_{min}	1525 nm
λ_{max}	1575 nm
D_{max} $[D(\lambda_{min}) \leq \lvert D_{max} \rvert \leq D(\lambda_{max})]$	3.5 ps/(nm x km)

Table 4: ITU-T G.655 CD specifications

Classification	D_{min} (ps/nm/km) at 1530 nm	D_{max} (ps/nm/km) at 1565 nm	Sign of D
G.655.A – C	1.0	10.0	+ or –
G.655.D	1.2	7.2	+
G.655.E	4.8	10.1	+

Table 5: ITU-T G.656 CD specifications

λ_{min} and λ_{max}	1460 and 1625 nm
Minimum value of D_{min}	2 ps/(nm x km)
Maximum value of D_{max}	14 ps/(nm x km)
Sign	Positive

From the specifications, the following table provides practical examples for CD for various fiber types. However, note that the CD can vary from these values for a given fiber type.

Table 6: Example dispersion characteristics of the different fiber types

ITU-T Fiber Type	Description	Zero Dispersion Wavelength	Example Dispersion at 1550 nm	Example Dispersion Slope at 1550 nm
G.652	Non-dispersion-shifted fiber	1300 – 1324 nm	~17 ps/nm/km	0.057 ps/nm²/km
G.653	Dispersion-shifted fiber	1500 – 1600 nm	0 ps/nm/km	0.07 ps/nm²/km
G.655.A – C	Non-zero-dispersion-shifted fiber	Not specified but ~1450 – 1480 nm	4 ps/nm/km	0.045 to 0.1 ps/nm²/km
	Negative non-zero-dispersion-shifted fiber		–5 ps/nm/km	0.05 to 0.12 ps/nm²/km

1.5 Chromatic Dispersion and Optical Transmission

1.5.1 Chromatic-Dispersion-Induced Pulse Spreading

Optical pulses travel through fiber in an array of wavelengths, typically around a central wavelength. Because the propagation speed depends upon the refractive index and the CD, the wavelengths can travel at different speeds. Those traveling faster arrive earlier than those traveling slower, resulting in a temporal broadening of the initial pulse. The effects of this phenomenon on the quality of optical transmission depend upon the bit rate of the signal, although, technologies and signal formatting have the greatest impact on signal tolerance to pulse spreading.

Figure 13 illustrates pulse spreading according to the data rates for a given amount of CD.

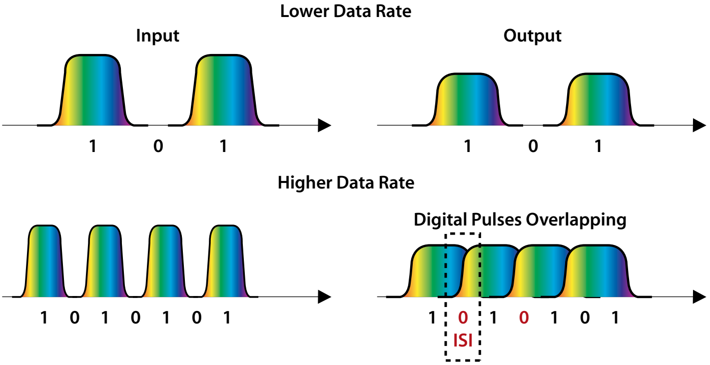


Figure 13: Schematic of pulse overlap according to data rate

For low data rate signals, the amount of CD does not significantly broaden the pulses into adjacent bit periods; therefore, the dispersion does not impact the proper discrimination of each bit.

With a higher data rate input, the pulses are shorter and closer together. When dispersion occurs, pulse spreading into adjacent bit periods makes it difficult to discern whether a pulse led to the occurrence of bit errors. This overlap into adjacent bit periods is referred to as inter-symbol interference (ISI), because it interferes with the proper reception of a neighboring bit.

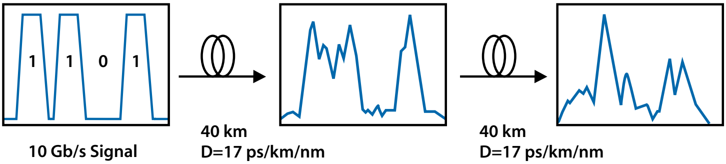


Figure 14: Example of a return-to-zero (RZ) 10-Gbps transmission signal through 2x40 km of G.652 fiber, where dispersion causes the pulses to spread and clearly overlap into adjacent bit periods

1.5.2 Limiting Transmission Parameter

1.5.2.1 Signal Bandwidth and Modulation Format

The modulation format used to encode the digital information onto the optical signal can significantly impact the tolerance of the signal to CD experienced during transmission. With the conventional encoding of digital information onto the amplitude of the optical signal (example of non-return-to-zero [NRZ]), both the optical bandwidth of the signal and the width of the optical pulses are directly related to the data rate of the signal. For higher data rates, the pulses are shorter and spaced closer together with a wider optical spectrum.

The impact of CD-induced pulse spreading becomes increasingly significant at higher data rates, as the shorter, closer-spaced pulses have less room to spread before overlapping into an adjacent bit period. Furthermore, given the wider spectrum, these pulses comprise a greater range of wavelength components, which travel at different speeds and, therefore, experience greater spreading.

These two effects, closer pulses and wider optical spectrum, decrease the optical signal's tolerance for CD by a factor of 4 when the data rate is doubled (assuming a constant modulation format). One factor of 2x less tolerance is due to half the spacing of half as many pulses. The other factor of 2x comes from the spectrum being twice as wide, due to the pulses being shortened by a factor of two.

Increasing the bit rate by a factor of 4 reduces tolerance to CD by a factor of 16.

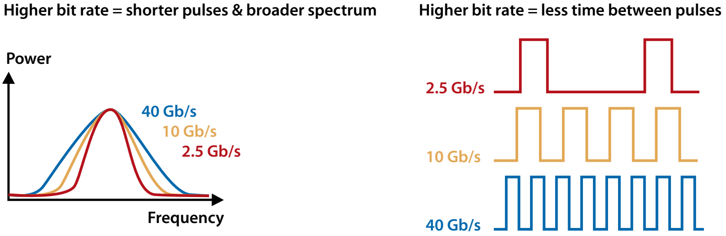


Figure 15: Effect of bit rate increase on pulse width and intervals

For example, a 10 Gbps signal can tolerate nominally 1/16th the amount of CD as a 2.5 Gbps signal assuming both use the same modulation format. However, note that different modulation formats and the methods of generating and modulating the encoded optical signals greatly impact a signal's tolerance for CD. Therefore, the tolerance of actual systems may not follow the same bit rate scaling as shown in the previous example. Typically, formats and methods that result in signals with greater tolerance for CD are used for higher bit rates simply to mitigate dispersion impairments.

Conventionally, amplitude modulation formats, such as NRZ and return-to-zero (RZ), have been used at 2.5 and 10 Gbps data rates. Modulation formats, such as duobinary and differential quadrature phase shift keying (DQPSK), are more robust against the impact of CD and are used at 10 and 40 Gbps data rates to overcome the dispersion impairments.

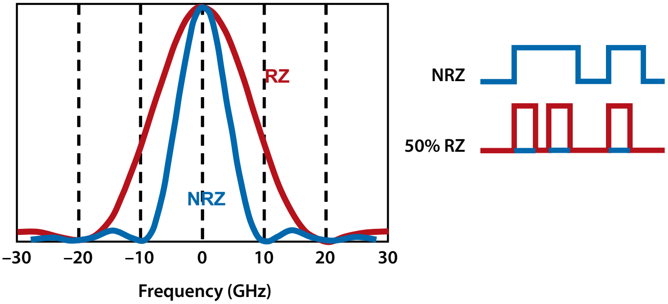


Figure 16: Optical bandwidth of a NRZ and 50 percent RZ amplitude modulated signal (both operating at the same data rate)

1.5.2.2 Chirped Signals

Turning the modulation source laser on and off can impact the amplitude modulation of a modulated signal, thus complicating the effects of CD. During the process, the output wavelength of the signal shifts slightly as the output power increases and decreases. This shift causes a frequency chirp that gives the laser an even wider optical spectrum as it introduces additional wavelength components on the leading and trailing edges of the pulse.

If these components are oriented such that the CD causes those at the leading edge of the pulse to travel faster and those at the trailing edge to travel slower, the pulse will broaden more rapidly than if the signal were not chirped. Therefore, the signal will have a weaker tolerance for chromatic dispersion. However, if the dispersion causes the leading edge components to travel slower than the rest of the pulse and the trail edge components to travel faster, this will compress the temporal width of the pulse and can result in an increased tolerance for dispersion compared to an unchirped signal. Note that these two cases, respectively, can be caused by using opposite signs of CD and, in some cases, frequency chirp is intentionally applied to improve dispersion tolerance.

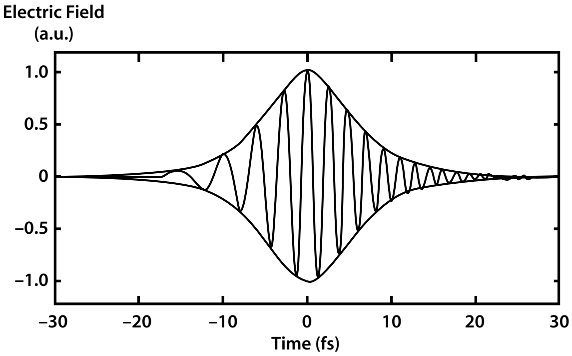


Figure 17: Electrical response of a chirp signal

1.5.3 Chromatic Dispersion Limits of Standardized Interfaces

For the standardized optical interfaces of synchronous optical network (SONET) transport systems, Telcordia common generic criteria GR-253-CORE defines the CD tolerance limits according to the bit rate per channel. It states that pulse broadening generated by the CD should not exceed 0.306 times the NRZ bit period. For synchronous digital hierarchy (SDH) interfaces, ITU-T G.957 and G.693 provide the tolerance limits.

The following table provides examples of these limits for a transmission at 1550 nm using NRZ coding with a power penalty of 1 dB.

Table 7: Maximum theoretical allowable CD for a transmission at 1550 nm with 1 dB penalty

Bit Rate/ Channel (Gbps)	Transmission		CD Tolerance at 1550 nm (ps/nm)
	SDH	SONET	
2.5	STM-16 (L-16.2)	OC-48 (LR-2)	18817
10	STM-64 (L-64.2)	OC-192 (LR-2)	1176
40	STM-256 (VSR-2000-3L)	OC-768 (SR-2)	73.5

Although non-standardized proprietary transmission interfaces have a specified maximum tolerable total CD, the values will vary significantly as different technologies are used to serve different transmission applications.

Considering Ethernet transmission, as defined by the IEEE 802.3ae-2002 standard, the tolerances for a 10 Gbps Ethernet transmission are much lower than SONET/SDH, which drives a tighter CD limit.

Table 8: Maximum theoretical allowable CD for a 10 Gbps Ethernet transmission at 1550 nm

Bit Rate/Channel (Gbps)	Transmission	CD Tolerance at 1550 nm (ps/nm)
10	Ethernet	738

1.5.4 Fiber Length Limitations Due to Chromatic Dispersion

CD is a linear effect that accumulates on a link linearly with distance. Consequently, the total CD on a longer fiber increases proportionally with the distance. The table below provides the maximum tolerance for total CD for each respective standardized interface.

Table 9: Maximum theoretical distance reach for G.652 and G.655 fiber types

Bit Rate/Channel (Gbps)	CD Tolerance at 1550 nm (ps/nm)	Max. Distance (km) for ITU-T G.652 Fiber Type	Max. Distance (km) for ITU-T G.655 Fiber Type
2.5	18817	>1100	>4700
10	1176	~70	~290
40	73.5	~5	~20

Similarly, proprietary transmission interfaces each have a total CD tolerance. Adequate link performance requires that the total chromatic dispersion for the entire fiber link be less than the maximum tolerable value.

As Subsection 1.4 showed, various fiber types and their dispersion coefficients may vary significantly within the range of defined ITU-T standards. Estimating the total dispersion of a given length of fiber can be accomplished by multiplying an assumed dispersion coefficient, such as the dispersion per unit length at a selected wavelength based on the fiber type, by the known length of the fiber. However, because assumptions about the fiber type and typical dispersion coefficient and dispersion slope are involved, there is risk of producing an inaccurate and undependable measure of the total CD.

In order to avoid assumptions and uncertainties about the fiber type and its typical dispersion characteristics, it is recommended to directly measure the total chromatic dispersion of a fiber.

1.6 Dealing with Excessive CD Values

CD is a linear parameter intrinsic to fiber, requiring compensation through insertion of an optical device into the link to produce opposite-sign dispersion to cancel the dispersion effects. For example, if the longer wavelength components traveled slower in the fiber relative to the shorter wavelength components, then within the compensating element, those longer wavelength components must travel faster.

Various techniques allow for compensation of CD. Passive CD accommodation (DA) technique, defined in ITU-T G.691, can be used in a long-haul, multi-span high-data-rate transmission system. A passive dispersion compensator (PDC, G.671) can be implemented using, in general, broadband dispersion compensation (dispersion-compensation fibers [DCF]) or narrowband dispersion compensation (fiber Bragg gratings).

Dispersion compensation can be incorporated into the optical transmitter, the optical receiver, and/or within an optical line-amplifier, which is currently the most common application.

To compensate the additional loss of the dispersion compensation modules (DCM), in-line amplifiers are commonly designed in dual-stage configurations with the DCM devices sandwiched between each stage, greatly increasing the optical signal-to-noise ratio (OSNR). ITU-T G.798 introduced this amplifier-aided dispersion accommodation process.

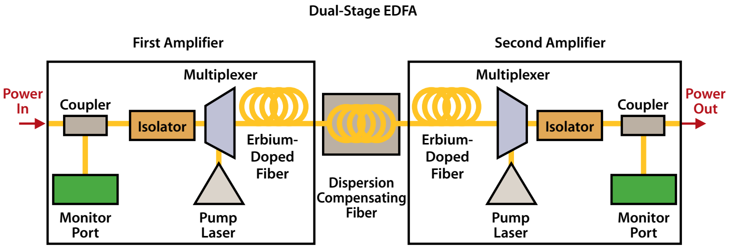


Figure 18: Schematic of a dual-stage amplifier with DCF inserted between the two stages

1.6.1 Broadband Compensation—Dispersion-Compensating Fiber

DCF is single-mode with a high negative CD value to compensate for the total dispersion in a given length of transmission fiber, such as G.652 or G.655. Similar to transmission fiber, the dispersion versus wavelength is continuous and can be engineered so that the slope of total CD for the length of DCF complements that of the transmission fiber. Therefore, the aggregated residual (or uncompensated) dispersion of the combined length of DCF and transmission fiber is both continuous and nearly zero.

Because the dispersion of the DCF versus wavelength is continuous, it does not limit the channel plan or channel bandwidth. Rather, DCF presents several advantages:

- offers a broadband dispersion compensation solution
- maintains near constant residual dispersion across the spectral region
- allows for configuration of counter dispersion by changing the fiber length
- offers a passive device with fixed dispersion values.

Drawbacks and other characteristics of DCF:

- typically provided in fixed lengths resulting in under- and over-compensation situations in an attempt to compensate for transmission fiber spans with a range of lengths and, therefore, total dispersion values
- significant optical loss added (0.6 dB/km of DCF) and generally bend-sensitive
- additional optical loss may require more complex optical amplifiers
- generally small core size of DCF causes high optical intensities and, therefore, a lower total power threshold for optical nonlinearities
- can cause additional polarization mode dispersion.

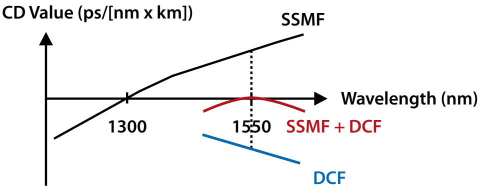


Figure 19: Example of dispersion with SSMF fiber (black line), dispersion with the same length of DCF (blue line), and the total residual dispersion (red line)

The specifications for DCF vary significantly among vendors. Table 10 shows a range of dispersion-compensating fiber modules.

Table 10: Example of technical specifications for JDSU Waveready DCF portfolio

Product	WRDCM-20	WRDCM-30	WRDCM-40	WRDCM-50	WRDCM-60
Optical Characteristics					
Insertion loss (dB)	2.7	3.3	4.0	4.3	5.4
Dispersion ±2% (ps/nm)	–325	–487	–650	–812	–974
PMD (ps)	0.29	0.36	0.42	0.45	0.51

1.6.1.1 Dispersion Slope Management and Compensation

In a multi-wavelength transmission system, DCF can compensate for CD in a given wavelength. However, if the dispersion slope compensation of the DCF is ineffective for the other transmission wavelengths, the combination may result in inadequate dispersion compensation for the other wavelengths. Applying dispersion compensation and dispersion slope compensation together can minimize the difference in residual dispersion between channels.

Figure 20 illustrates residual dispersion as a function of length, with and without dispersion slope compensation, on successive 80 km spans for three transmission wavelengths along each 80 km span. As the dispersion accumulates, a compensator is inserted to correct the dispersion back to zero. Without dispersion slope management in the first case, only the 1550 nm wavelength is compensated correctly. As the dispersion slope is not accounted for, the 1565 and 1530 nm wavelengths are either over or under compensated. In the second case, with proper dispersion slope compensation management, the compensation module provides different amounts of correction for each wavelength and all the wavelengths are correctly compensated.

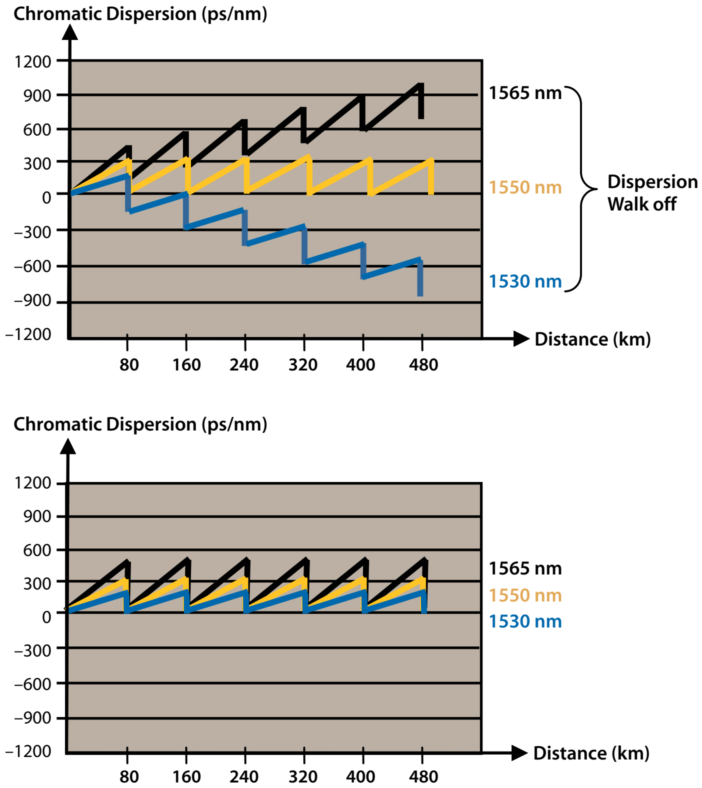
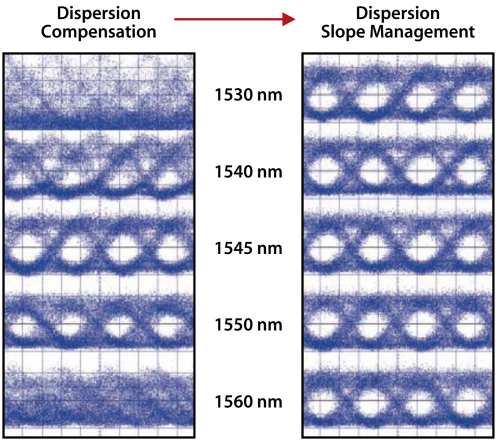


Figure 20: Difference between no slope management and slope management for three wavelengths being compensated with the same magnitude



Dispersion management precisely matches dispersion and dispersion slope to manage dispersion for any NZDSF or SMF fiber type over any span distance

Figure 21: Example of eye diagrams showing the impact of different dispersion compensated wavelengths with and without slope management

Both G.655 and G.652 fibers generally require dispersion compensation to span conventional distances in metropolitan, regional, and long-haul networks, operating at 10 Gbps or higher. As G.655 fiber has about 75% less dispersion than a G.652 fiber, it can enable a 4x improvement in the uncompensated reach, simply due to the lower dispersion per unit length.

1.6.2 Narrowband Dispersion Compensation—Fiber Bragg Gratings

These compensators are based upon chirped fiber Bragg gratings (FBG). FBGs are designed with a periodic variation of the refractive index (periodΛ). All the wavelengths satisfying the condition $\lambda B = 2\Lambda n_{eff}$ where B is an integer and n_{eff} is the effective refractive index of the host material (typically glass) are reflected and all others are passed through the device.

In order to produce dispersion within these devices, the period of the device is varied along the length of the fiber such that the shorter wavelengths are reflected at the near end of the fiber grating and longer wavelengths are reflected at the far end (or vice versa). The additional propagation delay versus wavelength produces the intended variation dispersion compensation for each wavelength. Figure 22 below illustrates this concept.

The FBG is then used in conjunction with a circulator to reroute the reflected light into an output fiber separate from the input fiber from which the light originated.

With current FBG technology, each channel is addressed with a specific segment of the grating. While these devices can address all channels within a band (such as the C-band), each channel has a finite usable bandwidth. This can cause design and performance limitations and does not allow modifications in the channel spacing.

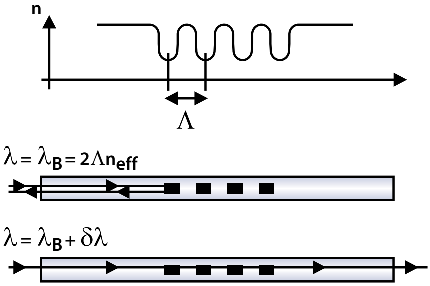


Figure 22: Schematic of a fiber Bragg grating

The FBG compensators bring several advantages such as:
- generally low insertion loss
- slope matching of G.652 and G.655 fibers
- compact design
- fully passive element
- no potential for optical nonlinearity.

Some drawbacks or at least some characteristics must be accounted for:
- finite operational bandwidth per channel
- fixed channel plan
- typically a greater error group delay ripple
- high cost for high count DWDM channel compensation.

1.7 Measuring Chromatic Dispersion

As CD is a major constraint in today's and tomorrow's telecommunications transmissions over the fiber, it is critical to characterize the fiber network in order to quantify the level of CD and understand the magnitude of compensation which will have to be implemented.

1.7.1 When to Perform Measurements

Although CD is a relatively unchanging phenomena reported by the fiber manufacturer, CD testing will likely be performed several times during the life cycle of the network.

During the manufacturing process, fiber manufacturers perform CD measurements to ensure proper fiber specifications for quality assurance.

CD measurement can also be performed after cable manufacturing to confirm fiber dispersion.

In the field, CD measurement is typically performed:
- during or just after the fiber installation
- before upgrade to higher bit rates in installed and operational spans in order to determine if and how much CD compensation is necessary
- prior to or after taking possession of leased or third party fiber, in order to know the fiber limits, and to select appropriate network elements (such as transmitters, amplifiers, compensators)
- during or after maintenance or repair to verify the type of fiber installed has not been changed unknowingly.

1.7.2 What Parameters are Measured

CD analyzers not only provide the CD values according to the wavelength but also other parameters, such as the zero dispersion wavelength. The results to be reported mainly depend on customer requirements. International standards provide the following list of parameters to be measured:

- dispersion coefficient values measured at certain specified wavelengths
- dispersion maximum (or maxima) over a specified range of wavelengths
- zero dispersion wavelength and dispersion slope at this wavelength.

1.7.3 Measurement Methods

The CD measurement process either provides direct CD values or group delay values as a function of wavelength. The CD value and dispersion slope are found from the derivatives of these data. The differentiation is most often done after the data are fitted to a mathematical model.

These test methods are described and standardized by the main standardization bodies: the IEC, TIA, and ITU-T. Test instrument calibration is defined in the IEC 61744 document and Telcordia has also published the GR-761-CORE requirements for a CD analyzer.

These documents describe several methods for measuring CD, several of which are not well suited to field testing. Currently three popular and effective field test methods fall into two categories: phase velocity measurement and group delay measurement. Several methods are used for CD measurements in the field.

Table 11: CD test methods and associated references

Standards	Description
IEC 60793-1-42	Measurement methods and test procedures—chromatic dispersion
ITU-T G.650.1	Definitions and test methods for linear, deterministic attributes of single-mode fiber and cable
TIA FOTP-175-B	CD measurement of single-mode optical fibers
GR-761-CORE	Generic criteria for chromatic dispersion test sets

1.7.4 Group Delay vs. Chromatic Dispersion

The phase shift and pulse delay methods measure the propagation delay (or group delay) at selected wavelengths and, from the measured delay versus wavelength data, interpolate the delay for other wavelengths not directly measured by using a numerical fitting algorithm (see Table 12). From the resulting fit of delay versus wavelength, the dispersion coefficient (the slope of this fit) and the dispersion slope as a function of wavelength are then extracted.

Several possible approximation equations exist that correspond to a particular fiber type and wavelength range. The network operator must understand which equation to apply according to the fiber under test and wavelength region of interest.

Table 12: Definition of approximation equations and coefficients

Fit Type	Equation for Group Delay	Equation for Dispersion Data
3-term Sellmeier	$A+B\lambda^{2}+C\lambda^{-2}$	$2B\lambda-2C\lambda^{-3}$
5-term Sellmeier	$A+B\lambda^{2}+C\lambda^{-2}+D\lambda^{4}+E\lambda^{-4}$	$2B\lambda^{2}-2C\lambda^{-3}+4D\lambda^{3}-4E\lambda^{-5}$
2nd order polynomial (quadratic)	$A+B\lambda+C\lambda^{2}$	$B+2C\lambda$
3rd order polynomial (cubic)	$A+B\lambda+C\lambda^{2}+D\lambda^{3}$	$B+2C\lambda+3C\lambda^{2}$
4th order polynomial	$A+B\lambda+C\lambda^{2}+D\lambda^{3}+E\lambda^{4}$	$B+2C\lambda+3C\lambda^{2}+4E\lambda^{3}$

Table 13: Slope equations (Table A2/ITU-T G.650.1)

Fit Type	Equation for Dispersion Slope
3-term Sellmeier	$2B+6C\lambda^{-4}$
5-term Sellmeier	$2B+6C\lambda^{-4}+12D\lambda^{2}+20E\lambda^{-6}$
2nd order polynomial (quadratic)	$2C$
3rd order polynomial (cubic)	$2C+6D\lambda$
4th order polynomial	$2C+6D\lambda+12D\lambda^{2}$

Table 14: Zero dispersion wavelength and slope equations (A.3/ITU-T G.650.1)

Fit Type	Zero Dispersion Wavelength	Zero Dispersion Slope
3-term Sellmeier	$(C/B)^{1/4}$	$8B$
2nd order polynomial (quadratic)	$-B/(2C)$	$2C$

Table 15: Approximation equation according to fiber type and wavelength range

Single-Mode Fiber Type	ITU-T Standard	Wavelength Range	Approximation
Dispersion unshifted fiber (standard fiber)	G.652	Around 1310 nm	3-term Sellmeier
		1550 nm region	Quadratic
		Full wavelength range (1260 –1640 nm)	5-term Sellmeier
Dispersion shifted fiber	G.653	1550 nm region	Quadratic
		Full wavelength range (1260 –1640 nm)	5-term Sellmeier
Non-zero dispersion shifted fiber	G.655	1550 nm region	Quadratic
		Full wavelength range (1260 –1640 nm)	5-term Sellmeier
Wideband NZDSF	G.656	Full wavelength range (1260 –1640 nm)	5-term Sellmeier
Mixed fibers	Including DCF	1550 nm region	Quadratic
		Full wavelength range (1260 –1640 nm)	5-term Sellmeier

Note 1: This table has been simplified for easier legibility. Please refer to IEC 61793-1-42 Ed2.0 for further details.

Note 2: Extrapolation to wavelengths outside the fitting region should be used carefully, as the correlation of the equations to actual fiber performance may diminish significantly.

Note 3: Investigations have shown that in practice the fit coefficient will be small over the wavelength range 1200 to 1600 nm. Therefore, a simplified four-term fit could also be used.

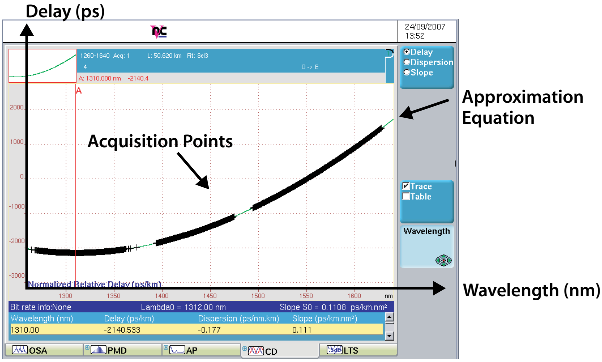
1.7.5 The Phase Shift Method

This is the reference test method defined by ITU-T G650.1 and IEC 60793-1-42.

1.7.5.1 Measurement Principle

The modulated light is sent over the fiber under test. The phase of the test signal is compared to the phase of a reference signal used to modulate the input signal. The phase difference measurement is performed versus wavelength over the entire wavelength range of the source.

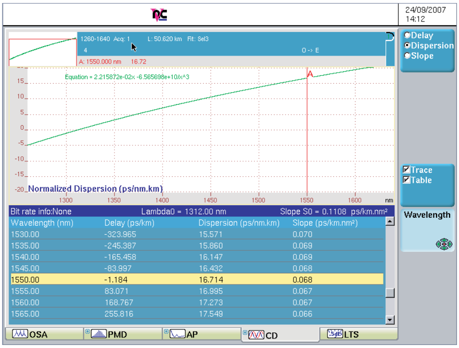
The group delay (or difference in arrival time versus wavelength) is calculated from the phase shift measurement of the modulated signal at the multiple wavelengths utilized. The group delay versus wavelength is fitted to the data using one of the approximation equations discussed above. The Phase Shift method utilizes either a “swept” source or a broadband source (or source array) and, in general, yields many more actual data points than the Pulse Delay method.



Bit rate info:None Lambda0 = 1312.00 nm Slope S0 = 0.1108 ps/km.nm²

Wavelength (nm)	Delay (ps/km)	Dispersion (ps/nm.km)	Slope (ps/km.nm²)
1310.00	-2140.533	-0.177	0.111

The CD is computed by calculating the slope of the group delay curve as a function of wavelength.



Bit rate info:None Lambda0 = 1312.00 nm Slope S0 = 0.1108 ps/km.nm²

Wavelength (nm)	Delay (ps/km)	Dispersion (ps/nm.km)	Slope (ps/km.nm²)
1530.00	-323.965	15.571	0.070
1535.00	-245.387	15.860	0.069
1540.00	-165.458	16.147	0.069
1545.00	-83.997	16.432	0.068
1550.00	-1.184	16.714	0.068
1555.00	83.071	16.995	0.067
1560.00	168.767	17.273	0.067
1565.00	255.816	17.549	0.066

Figure 23: Example of the JDSU Phase Shift method display: CD over the wavelength and approximation equation used (in green)

1.7.5.2 Test Equipment Setup

The transmitting end of the Phase Shift method requires a broadband source, or a tunable laser source, or a series of laser sources of different wavelengths that is amplitude modulated. At the receiver end, this method requires an optical detector (PIN or APD diode) operating in the transmitter range, an amplifier (may be used to increase the detection system sensitivity), and a phase meter which measures the phase of the incoming amplitude-modulated signal. The modulated phase is then processed and computed to provide the relevant CD values over the wavelength range.

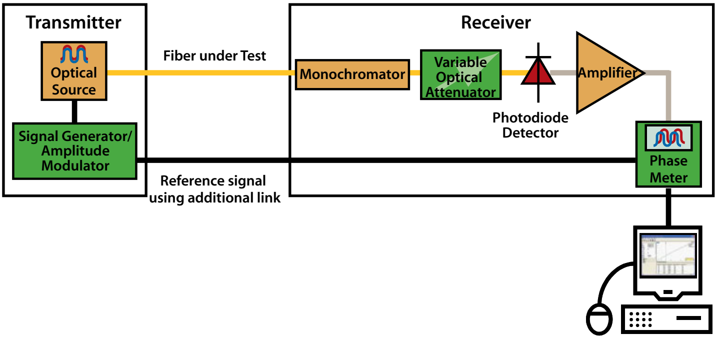


Figure 24: Typical schematic of the elements of the Phase Shift method

1.7.5.3 JDSU Phase Shift Solution

JDSU has developed a Phase Shift method which allows using only one fiber for carrying the reference and the test signal, simplifying the test procedure and offering a high performance, portable test solution for field applications.

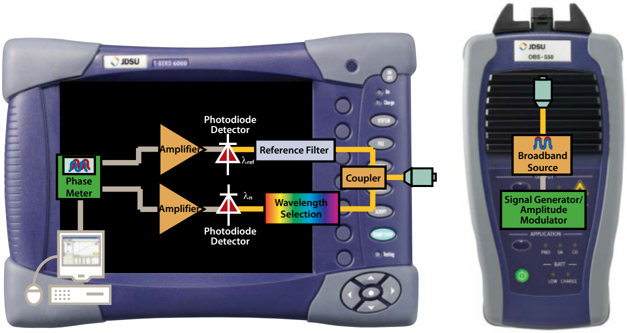


Figure 25: JDSU Phase Shift solution: T-BERD®/MTS-6000 platform with ODM module and its associated broadband source

1.7.5.4 Benefits and Limits

The Phase Shift method provides a significant set of advantages, including:

- high accuracy measurements
- high dynamic range (40 dB+) (>15 dB higher than the Pulse Delay method)
- high measurement repeatability
- compatible with non-bidirectional components (such as Erbium-Doped Fiber Amplifier [EDFA]).

Some limitations of the Phase Shift method include:

- measurement time can depend on the number of data points
- requires two units, one at each end
- dispersion versus length information not provided—not enabling the fiber link to be sectionalized
- fiber length must be known or measured separately to calculate the average CD coefficient (for example, using an optical time domain reflectometer [OTDR]).

Figure 26: Example of a JDSU Phase Shift analyzer (Plug-in Module), inserted in the T-BERD/MTS-6000 platform: the smallest dispersion tester in the marketplace

1.7.6 Spectral Group Delay in the Time Domain

This measurement method is also called "Time of Flight" or "Pulse Delay."

1.7.6.1 Measurement Principle

The fiber CD coefficient is derived from the measurement of the relative group delay experienced by the various wavelengths during propagation through a known (or measured) length of fiber.
The group delay is measured in the time domain by detecting, recording, and processing the delay experienced by pulses at various wavelengths.

The CD may be measured at a number of fixed wavelengths or over a wavelength range.

1.7.6.2 Test Equipment Setup

The Pulse Delay method requires a series of pulsed laser sources with different wavelengths or a pulsed tunable laser source, a variable attenuator, a photodetector, and a sampling oscilloscope.

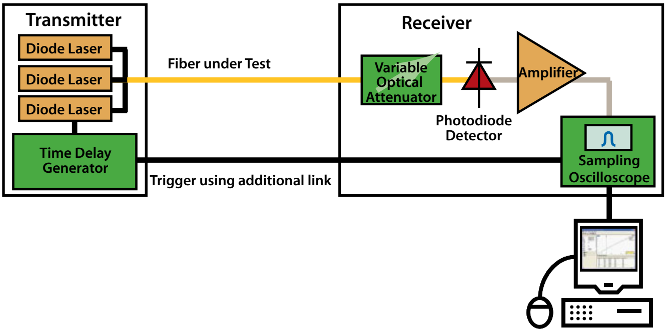


Figure 27: Typical schematic of the elements of the Pulse Delay method

An alternative solution is the use of an OTDR with multiple lasers or tunable laser. Another similar method is photon counting with the use of Bragg gratings.

Measurement Principle Using an OTDR

The OTDR sends pulses of four or more wavelengths into one end of the fiber. The relative arrival time is then measured for each backscattered wavelength signal. The first wavelength is used as a reference and compared with arrival times of the other wavelengths.

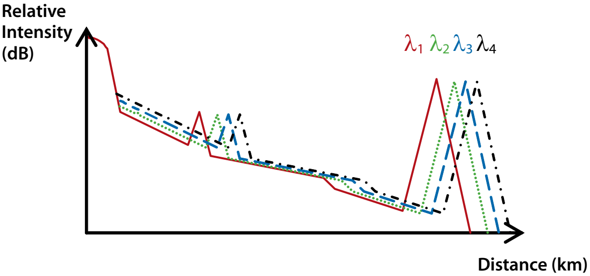


Figure 28: Multi-wavelength OTDR traces of a Pulse Delay method

The group delay versus wavelength is fitted to the data using one of the approximation equations discussed above. The CD is then computed by calculating the slope of the group delay curve as a function of wavelength.

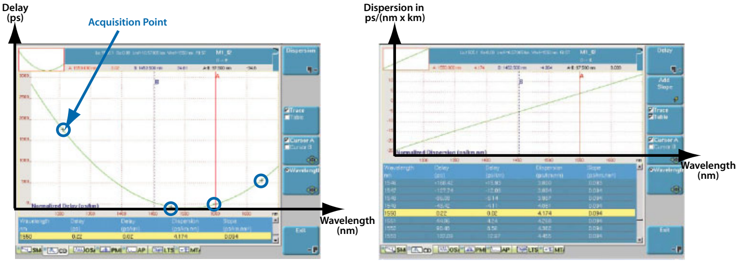


Figure 29: JDSU measurement displays

Note: The use of OTDR with four wavelengths complies with the industry standards. The IEC60793-1-42 states: "Investigations have shown that in practice the approximation coefficient will be small over the wavelength range 1200 nm to 1600 nm. Therefore, a simplified four-term fit can also be used"… also …"The measurement wavelengths shall span the zero dispersion wavelength, λ_0, or contain at least one point within 100 nm of λ_0 to use these data for calculation of λ_0."

Consequently, the use of the OTDR with four wavelengths including one in the 1310 nm region is well adapted for G652 fiber CD measurement and qualifying the zero wavelength value. Using the time of flight solution with only the C or C+L band will prevent measuring the zero wavelength around 1310 nm with confidence.

Figure 30: JDSU Pulse Delay OTDR method in the T-BERD/MTS-6000 platform

1.7.6.3 Benefits and Limits

The Pulse Delay method using OTDR provides three main advantages:

- requires access to only one end of a link (as it analyses reflected light of the fiber end reflectance peak)
- detects regions of different dispersion within a link, as it can analyze reflections at intermediate points (only if reflectances are present mid-span)
- combines an OTDR allowing a simultaneous distance and loss measurement (automatic measurement of distance as CD given per kilometer).

The scope of application is much narrower than the other methods as:

- distance range is limited by the end reflection: the higher the reflectance, the longer the distance. Not suitable for spans with APC connectors installed. The use of a reflective terminator is needed to reach medium to long distance and the test becomes two-ended.
- not suitable for long-haul or high-loss fiber link (>30 dB).
- not compatible with non-bidirectional components (such as EDFAs).

General Comments on Time of Flight

Accuracy of the time-of-flight method is not only determined by the number of wavelengths and fitting equation utilized but is also a function of the dispersion, distance, and pulse width. Distances greater than several kilometers are required to cause sufficient time delay between the pulses, and thus this method is not suited particularly well for short fiber lengths (<10 km). Therefore, it is important to use wavelength widely spaced to each other. For example, using only wavelengths in the same region (for example, C-Band) will even further limit the use of this method for short fibers, increasing the minimum distance.

1.7.7 Differential Phase Shift

This test method is defined by ITU-T G650.1 and IEC 60793-1-42.

1.7.7.1 Measurement Principle

In this method, the relative group delay difference between the two wavelengths is determined by measuring the difference in the phase of the amplitude modulated signals of two closely spaced wavelengths after propagating through the fiber under test (FUT). The CD at a wavelength medial to the two test wavelengths is then given by the group delay difference divided by the wavelength separation of the two sources.

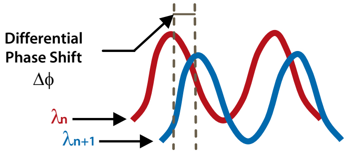


Figure 31: Schematic of Differential Phase Shift measurement

This process is then repeated with several wavelengths pairs in the test range producing a curve of CD versus wavelength.

1.7.7.2 Test Equipment Setup

The Differential Phase Shift method requires a tunable laser source (or a series of laser sources of different wavelengths) that can be amplitude-modulated and an optical detector to measure the relative phase of the amplitude modulation.

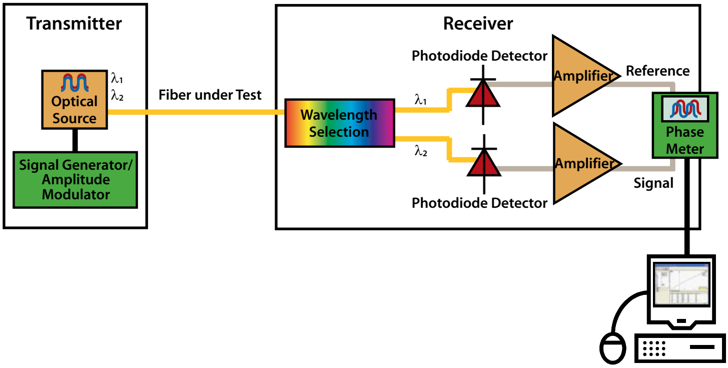


Figure 32: Typical schematic of the elements of the Differential Phase Shift method

1.7.7.3 Benefits and Limits

This method provides similar advantages to the Phase Shift method, including:

- direct dispersion measurement
- high accuracy measurements
- high dynamic range (40 dB+) (>15 dB higher than the Pulse Delay method)
- large number of data points can be collected, minimizing reliance on interpolation
- high measurement repeatability
- compatible with non-bidirectional components (such as EDFAs).

But there are some drawbacks:

- measurement time can depend on the number of data points
- two units required, one at each end
- dispersion versus length information not provided, not enabling the fiber link to be sectionalized
- fiber length must be known or measured separately to calculate the average CD coefficient
- tunable laser technology typically limits measurement to a given band (such as C-Band) unless multiple tunable lasers are used, which can increase cost.

1.7.8 Measurement Applications

Because of the performance differences between each measurement method, when choosing a CD analyzer it is important to match its capabilities to the specific application. The suitability of methods to specific applications is compared in Table 16.

Table 16: Test method suitability according to the application

Application	Phase Shift	Diff. Phase Shift	Pulse Delay
Standard fiber G652	✓	✓	✓
Dispersion shifted fiber G653	✓	✓	✓
NZDSF G655	✓	✓	✓
Mix of fiber types	✓	✓	×
Medium distance and metro networks (<80 km)	✓	✓	✓
Long-distance network (>120 km)	✓	✓	×
CD compensators qualification	✓	✓	✓
Amplified links testing	✓	✓	×
Short distances (<10 km)	✓	✓	×

Attention should be paid to portability, autonomy (battery powered), ease of use, set up time, warm up time, and degree of operator intervention, among other factors.

Polarization Mode Dispersion (PMD)

Chapter 2

When installing a new fiber optic network or upgrading an existing network to higher bit rate, the quality and properties of the optical fiber determine the suitability of this network to carry a defined transmission speed. Polarization mode dispersion (PMD) may pose severe limits on the transmission of higher data rates over existing fiber infrastructure. As a result, PMD measurements have become an essential part of the fiber characterization process. Although the detailed effects of PMD on the transmission of optical signals are highly complex, the average amount of PMD (mean differential group delay [DGD]) in any given fiber can be accurately assessed through relatively simple measurements.

2.1 Fiber Birefringence

PMD is caused by local birefringence (or double refraction) in the fiber, which may arise from a combination of material and waveguide birefringence. If a fiber exhibits different indexes of refraction (IOR) based on the polarization state (rotational orientation with respect to the fiber axis) of the transmission signal, then this fiber is said to be birefringent. The differing IORs lead to differing velocities of propagation of the modes. In silica optical fibers, material birefringence is typically the result of internal or external stress in the fiber core, introduced in the fiber manufacturing process or in the fiber cabling process through bending and twisting.

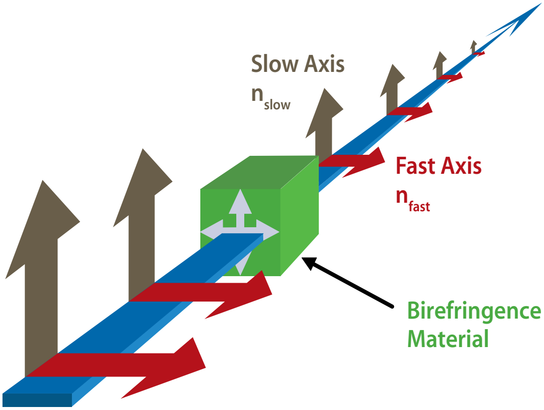


Figure 33: Propagation in a birefringence material

Waveguide birefringence, on the other hand, results from imperfections in the geometry of the fiber core and/or cladding, usually introduced in the manufacturing process.

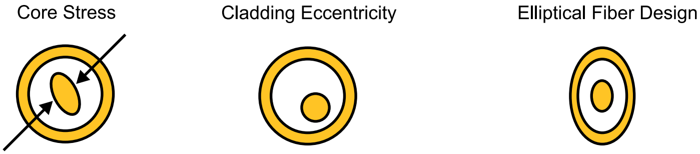


Figure 34: Imperfect fiber design causes birefringence

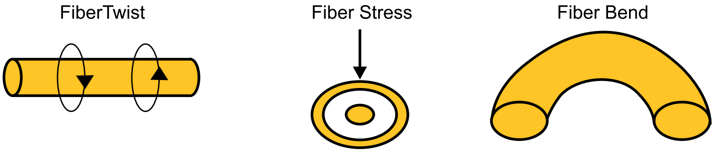


Figure 35: External stress causes birefringence

Note that some fibers, such as polarization maintaining fibers (PMFs), are intentionally designed to be highly birefringent. In such fibers, the velocity of propagation (speed of light) varies substantially with the polarization state of the launched signal.

2.2 Definition of PMD

Polarization mode dispersion, or PMD, is defined as the temporal spreading of the transmission signal pulses due to birefringence. PMD is generally conceptualized and mathematically modeled as the resulting differential time delay between signal components that is transmitted in two well-defined orthogonal polarization states, or principal states of polarization (PSPs) of the fiber. The two PSPs propagate at different speeds through the fiber. This creats two time-delayed copies of the launched signal that may cause severe distortion in the optical receiver at the end of the fiber. Furthermore, PMD may vary with time and with optical frequency due to higher-order PMD effects. Therefore, signals transmitted over different wavelength channels of a given fiber usually experience different amounts of distortion.

2.2.1 Differential Group Delay

The difference in arrival time between the two principal modes of polarization (known as Eigen modes of the fiber) is known as birefringence. Fibers always exhibit two orthogonally polarized modes that traverse the fiber at largely different speeds. They introduce a differential time delay between optical signal components that are transmitted in these two modes. The magnitude of PMD in a fiber is usually expressed as this difference that is known as the DGD and is usually denoted as $\Delta\tau$ (delta tau).

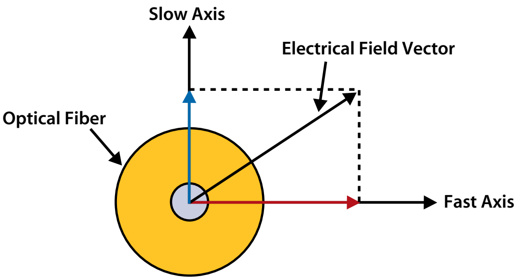


Figure 36: Signals transmitted through a birefringent fiber experience a slow and fast polarization mode

Therefore, a short signal pulse transmitted through a highly birefringent fiber may be decomposed into two orthogonally polarized pulses that travel at different speeds through the fiber, as shown schematically in Figure 37.

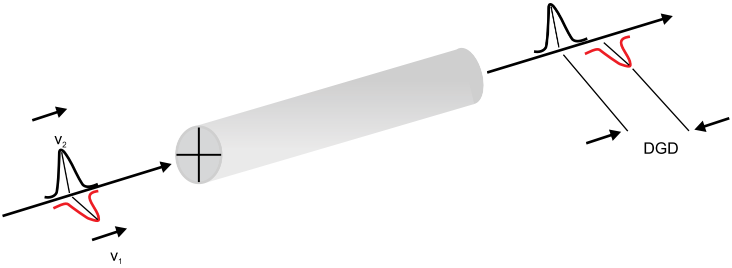


Figure 37: Differential group delay in a highly birefringent fiber

2.2.2 Polarization Mode Coupling

With the exception of polarization-maintaining fibers, utilized for special transmission schemes, most conventional optical fibers employed in telecommunications systems are designed to have minimal birefringence. Nevertheless, individual telecommunications fibers may exhibit noticeable amounts of birefringence caused by residual material or waveguide birefringence. But unlike in highly birefringent polarization maintaining fibers, the birefringence causing PMD is not uniform along the fiber because of random polarization mode coupling introduced by micro-bending or twisting of the fiber. Rather, these fibers may be viewed as being composed of many short lengths of birefringent fibers whose fast and slow polarization axes are randomly oriented. The random orientation of the individual fiber pieces in this model causes the same effects as random polarization mode coupling in real fibers.

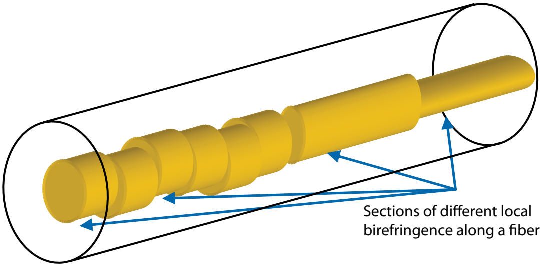


Figure 38: Fiber birefringence in an optical fiber link

Such a fiber does not exhibit well-defined polarization modes. In fact, the polarization transfer matrix of such a fiber is an extremely complicated function of optical frequency. Nevertheless, it can be shown that PMD fibers can always be modeled as two orthogonal launch polarization states that introduce minimal distortion in a transmitted signal—just like the Eigen modes of a birefringent fiber. A differential time delay is introduced between signal components that are transmitted in these two PSPs. It should be noted, though, that—unlike the Eigen modes of birefringent fibers—the two PSPs change their orientation along the fiber. In addition, the orientation of the PSPs changes randomly with optical frequency.

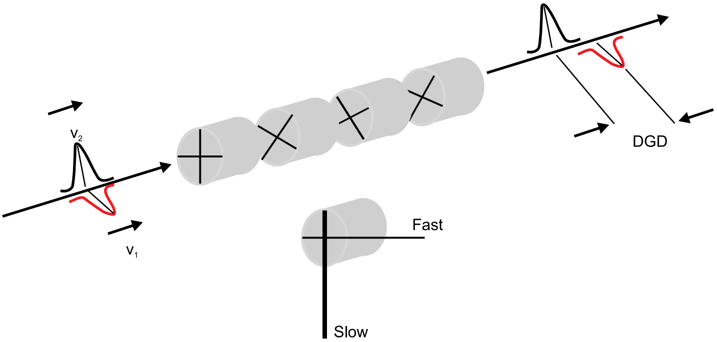


Figure 39: Strong mode coupling in telecommunications optical fiber

2.2.2.1 Weak Polarization Mode Coupling

Individual birefringent components with only weak or no polarization mode coupling, such as isolators, couplers, or short lengths of optical fiber, usually exhibit little or no wavelength dependence in the DGD. Furthermore, the DGD of these elements scales linearly with the length of the device.

2.2.2.2 Strong Polarization Mode Coupling

Standard telecommunications fibers usually exhibit strong polarization mode coupling. As a result, the DGD in these fibers varies randomly with optical frequency. Moreover, the average DGD in these fibers scales with the square root of the fiber length.

2.2.3 Wavelength Dependence of the DGD

In fibers with strong polarization mode coupling, the DGD and the PSPs vary randomly with optical frequency, as shown in the example of Figure 40. Similar random variations can be observed with changes in the temperature of the fiber. Often, the wavelength dependence of the DGD changes dramatically with just a few degrees of temperature variation. Similarly, manual handling of the fiber may also change the DGD and its frequency dependence. As a result, the DGD at any given wavelength is not constant with time and may change randomly.

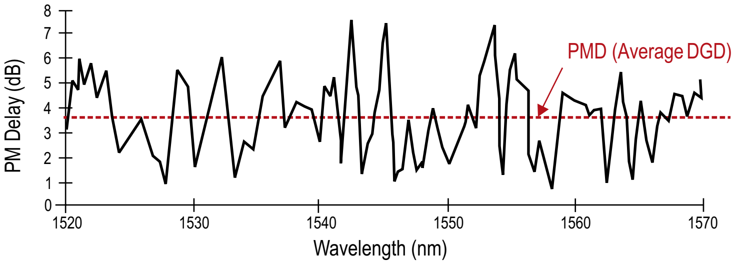


Figure 40: DGD as a function of optical wavelength

2.2.4 Probability Distribution of the DGD

In long optical fibers (with sufficient random polarization mode coupling), the random DGD variations with optical frequency or temperature usually exhibit a Maxwellian probability distribution, as shown in Figure 41. Hence, the probability density function for Δτ is given by

$$\sqrt{\frac{2}{\pi}}\frac{\Delta\tau^2}{\alpha^3}\exp\left(-\frac{\Delta\tau^2}{2\alpha^2}\right)$$

where $\alpha = \sqrt{\pi/8}\,\langle\Delta\tau\rangle$ is proportional to the mean DGD $\langle\Delta\tau\rangle$.

Therefore, for any given fiber, a single measurement of the mean DGD fully characterizes the statistical distribution of the DGD in the fiber.

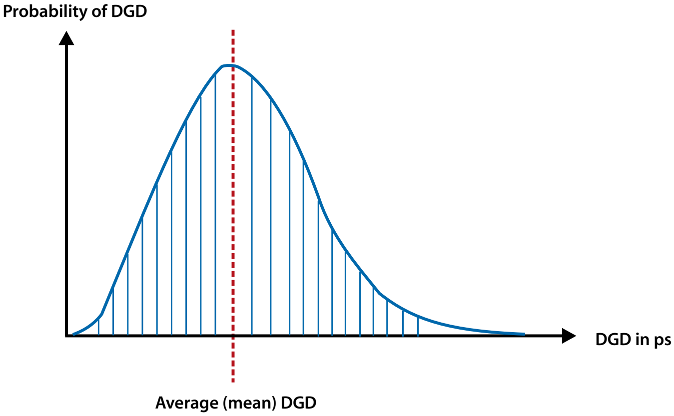


Figure 41: Maxwellian probability distribution of the DGD

2.2.5 Mean DGD and PMD Coefficient

The fastest and most common method for measuring the mean DGD $\langle \Delta\tau \rangle$ of a fiber is to measure the DGD variations as a function of frequency over a wide range of different wavelengths, as explained in more detail below. For long optical fibers with strong polarization mode coupling, the mean DGD scales with the square root of the total fiber length. This means that if a fiber is shortened to only 25 percent of its original length, the mean DGD decreases to only 50 percent of its original value. According to this scaling law, the mean DGD of a fiber is usually characterized by a normalized PMD coefficient, given by

$$\langle \Delta\tau_c \rangle = \langle \Delta\tau_c \rangle / \sqrt{L}$$

This is typically expressed in units of $ps/\sqrt{km}$ where L is the fiber length.

2.2.6 Second-Order PMD

Second-order PMD is an extension of first-order PMD that characterizes the wavelength dependence of the DGD and the PSPs. Both effects are summarized by a single second-order PMD parameter

$$\tau_\omega = \sqrt{\tau_{\omega\|}{}^2 + \tau_{\omega\perp}{}^2}$$

which is usually expressed in units of ps^2 or ps/nm, wherein $\tau_{\omega\|}$ is proportional to the first frequency derivative of the DGD and $\tau_{\omega\perp}$ characterizes the first-order frequency dependence of the PSPs. Just like the DGD $\Delta\tau$, the second-order PMD parameter τ_ω varies randomly with optical frequency and temperature. Its statistical variations are described by the following equation:

$$\frac{\sigma^2\,\tau_\omega}{\pi}\,\frac{\tanh(\sigma\,\tau_\omega)}{\cosh(\sigma\,\tau_\omega)}$$

where the parameter σ is related to the mean second-order PMD parameter $\langle \tau_\omega \rangle$, which in turn is related to the mean DGD as

$$\langle \tau_\omega \rangle \approx \langle \Delta\tau \rangle^2 / \sqrt{12}$$

Hence, the mean second-order PMD parameter $\langle \tau_\omega \rangle$ is proportional to the square of $\langle \Delta\tau \rangle$ and, consequently, scales linearly with fiber length. It should be noted that the second-order PMD parameter is sometimes expressed as a differential value of twice the magnitude of τ_ω, such as $\Delta\tau_\omega = 2\,\tau_\omega$ and $\langle \Delta\tau_\omega \rangle = 2\langle \tau_\omega \rangle$.

Second-order PMD normally becomes important when the mean DGD $\langle \Delta\tau \rangle$ is substantially larger than 15 percent of the bit period of the transmitted optical signal. It thus poses a limit on first-order PMD compensation. Excessive second-order PMD also reduces the tolerance of a transmitted signal to chromatic dispersion.

Note that the impact of second-order PMD on the transmission of optical signals is not yet fully understood.

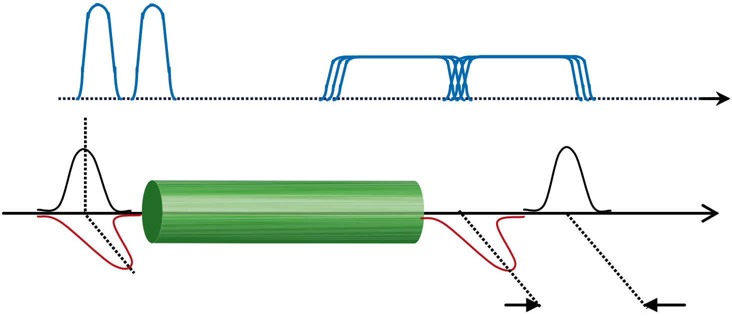


Figure 42: Typical signal distortions caused by excessive PMD in a fiber transmission line

2.2.7 PMD-Induced System Outages

Excessive PMD in a fiber optic link generally causes pulse broadening or jitter in the received electrical signal, as shown schematically in Figure 42. As a result, errors may occur in the decoding of the signals. These transmission impairments increase with the magnitude of the instantaneous DGD $\Delta\tau$. If the mean DGD exceeds certain known limits by a small amount, sometimes it is sufficient for additional margins to be allocated in the system design to cope with signal distortions caused by PMD. Typically, an extra margin of 1 to 3 dB may be added to the optical signal-to-noise ratio (OSNR) at which the system operates reliably. However, no matter how large this margin is, there always exists a finite probability that the randomly fluctuating DGD in the fiber becomes larger than the maximal value at which the system operates error free, in which case the system has to be taken out of service.

The likelihood of such an outage to occur is called the outage probability that may be calculated for any given transmission system based on the mean DGD in the fiber, the allocated OSNR margin, and the sensitivity of the signal to instantaneous DGD. Conversely, given a maximal tolerable outage probability (typically in the range between 10^{-5} and 10^{-7}), one may calculate the maximal tolerable average DGD in the transmission link, as shown schematically in the Figure 43.

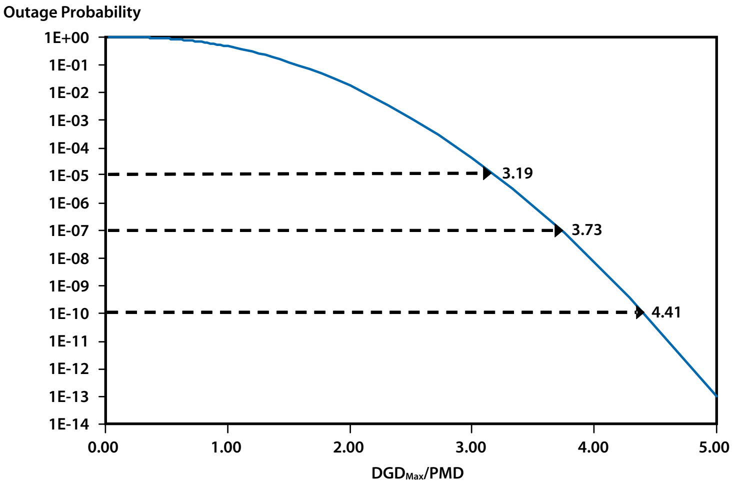
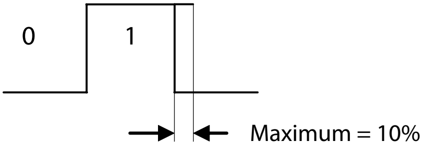


Figure 43: Outage probability vs $\mathrm{DGD}_{\mathrm{Max}}$/PMD

As a rule of thumb, most digital transmission systems can tolerate mean DGD of up to one tenth of the bit period T_b of the digital information signal, $\langle \Delta\tau \rangle_{max} = T_b/10$. This rule was originally derived for NRZ-formatted on-off-keyed signals and assumes an OSNR margin of 1 dB as well as an outage probability of 10^{-6}. RZ-formatted signals, on the other hand, are substantially more tolerant to first-order PMD and, hence, exhibit higher values for $\langle \Delta\tau \rangle_{max}$.



For example, 10 Gbps SONET/SDH transmission exhibits a bit length 100 ps which derives to a 10 ps maximum delay.

2.2.7.1 Distance Limitations

Once $\langle \Delta\tau \rangle_{max}$ is known for a specific modulation format and transmission system, one may then calculate the maximal allowable PMD coefficient as a function of the transmission distance *L*.

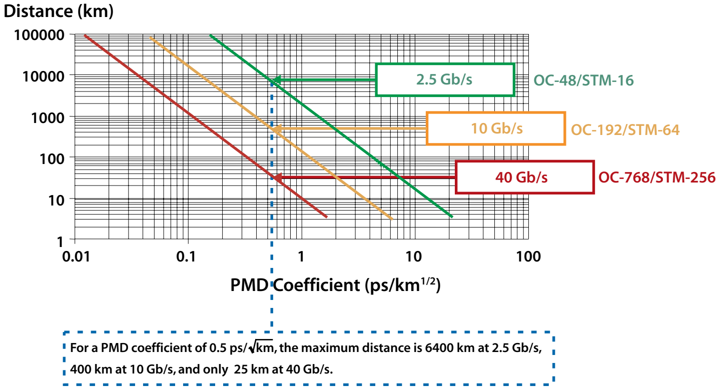
$$\langle \Delta\tau_c \rangle_{max} = \langle \Delta\tau \rangle_{max} \sqrt{L}$$

As an example, Table 17 lists the maximal PMD coefficient for NRZ-formatted SONET and SDH signals that are transmitted over a distance of 400 km for three different bit rates.

Table 17: Maximal mean DGD as a function of bit rate

Bit Rate (Gb/s)	SDH Format	SONET Format	Bit Period (ps)	Max. Mean DGD (ps)	PMD Coefficient for $L = 400$ km ($ps/\sqrt{km}$)
2.5	STM-16	OC-48	400	40	<2
10	STM-64	OC-192	100	10	<0.5
40	STM-256	OC-768	25	2.5	<0.125

The maximal allowable PMD coefficient decreases linearly with increasing bit rate. This can be clearly seen in Figure 44, which displays the maximal PMD coefficient as a function of transmission distance for the three different bit rates.



For a PMD coefficient of 0.5 ps/$\sqrt{km}$, the maximum distance is 6400 km at 2.5 Gb/s, 400 km at 10 Gb/s, and only 25 km at 40 Gb/s.

Figure 44: Maximum distance as a function of PMD coefficient and bit rate

2.3 PMD in 40 Gbps Transmission Systems

As described above, the sensitivity of digital optical information signals to PMD increases linearly with bit rate. Therefore, 40 Gbps signals are 4 times more sensitive to PMD than 10 Gbps signals and 16 times more sensitive than 2.5 Gbps signals. Hence, PMD tolerance is an important parameter to be specified in 40 Gbps systems. However, the PMD tolerance also depends on the modulation format. This can be seen in Figure 45 which displays the OSNR penalty as a function of instantaneous DGD for three different on-off-keyed (OOK) modulation formats. Figure 45 shows that RZ-formatted OOK signals are more tolerant to DGD than NRZ-formatted signals. Furthermore, RZ signals having a narrow pulse width of 33% of the bit period (FWHM) are substantially more tolerant to DGD than carrier-suppressed RZ (CS-RZ) signals with a pulse width of 67% of the bit.

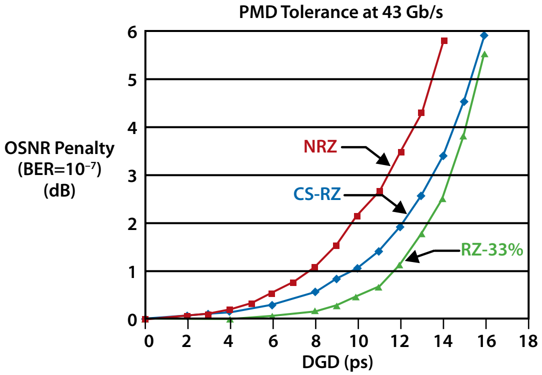


Figure 45: OSNR penalty vs. DGD for different line codes

In general, the shorter the transmitted pulses are, the more instantaneous DGD a signal can tolerate. However, the above results were obtained with a first-order PMD emulator that generates pure DGD but no second-order PMD, just like a highly birefringent fiber. The sensitivities to real fiber PMD may deviate significantly from the above results, because CS-RZ-formatted signals are more tolerant to second- and higher-order PMD than RZ-formatted signals. Similarly, NRZ-formatted signals are more tolerant than CS-RZ-formatted signals.

2.4 PMD in 10-Gigabit Ethernet Systems

Deployment of 10 Gbps Ethernet technology is showing up widely in high-performance Local Area Networks (LANs) as well as in Metropolitan Area Networks (MANs) and Wide Area Networks (WANs). Ethernet technology supports many types of traffic, such as data, voice, and video over IP, and can be interfaced with conventional SONET/SDH or ATM networks. In general, optical Ethernet signals are affected by the same dispersion phenomena as discussed above. However, there are some small but important differences in the PMD tolerance of Ethernet signals when compared to standard SDH/SONET transmission.

2.4.1 Maximal PMD Tolerance

Ethernet systems do not allow outage probabilities larger than 10^{-7}. As a result, $\langle \Delta\tau \rangle_{max}$ cannot exceed 26.8% of the maximal tolerable instantaneous DGD $\Delta\tau_{max}$. Assuming $\Delta\tau_{max}$ =19 ps for a 10-Gbps Ethernet system, $\langle \Delta\tau \rangle_{max}$ is approximately 5 ps.

If we compare 10-Gbps Ethernet to 10-Gbps SDH/SONET transmission limits, we see a tighter dispersion tolerance for 10 GigE as defined by the IEEE 802.3ae-2002 standard. There are two main reasons for that, reasons which apply for the CD as well:

- Forward error correction (FEC) is not robust compared with the one applied to 10-Gbps SDH/SONET
- Acceptable outage probability is lower: 1E-7 for 10 GigE vs 1E-5 for SDH/SONET

The graph in Figure 46 compares 10 GigE and 10 Gbps SDH/SONET and the related outage probability caused by PMD.

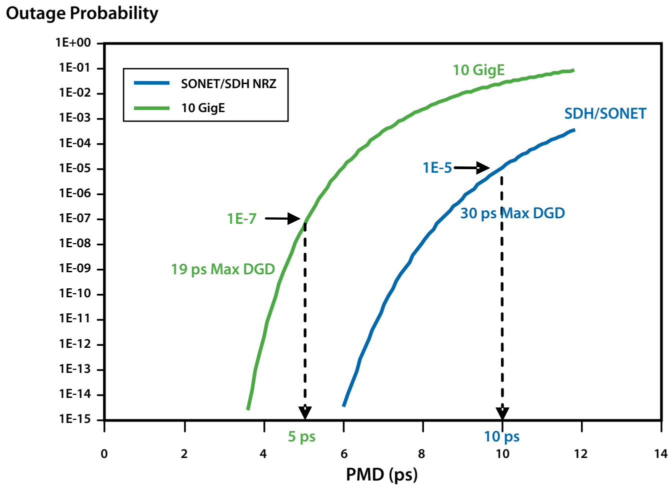


Figure 46: Outage probability at 10 Gbps Ethernet and SDH/SONET transmission

Figure 46 illustrates that the PMD limit is much tighter for 10 Gbps Ethernet signals than for 10 Gbps SDH/SONET signals, such as 5 ps compared with 10 ps for the SDH/SONET.

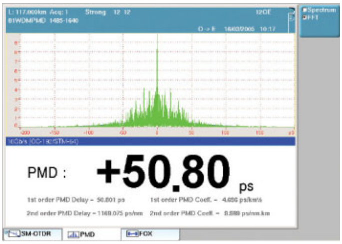
2.4.2 PMD Variations with Fiber Vintage

PMD remains a worrisome problem even in the most recent fiber installations.

The distribution of PMD values for operating fibers varies highly from installation to installation.

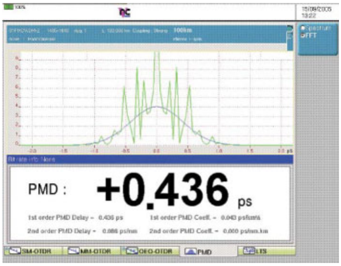
- USA: only 2% of fiber cables <1987 present PMD issues for one major operator.
- Europe: old fibers are not even suitable for 2.5 Gbps.

These two tests are examples of what could appear in any particular case.


PMD : +50.80 ps

1st order PMD Delay = 50.801 ps

Figure 47: 117 km G.652 fiber link employing fiber manufactured before 1990


PMD : +0.436 ps

1st order PMD Delay = 0.436 ps

Figure 48: 100 km G.652 fiber link employing new fiber manufactured in 2002

2.4.3 Fiber Links with High PMD

If a measurement reveals that the PMD in a certain fiber link exceeds a predetermined maximal value, then there are only a few options available to remedy this problem. Unlike for CD, there are no simple (or low-cost) solutions available to compensate for large amounts of PMD. Optical PMD compensators are currently under development but have not been deployed in the field thus far. Other possible remedies include:

- transmitting signals at lower bit rates
- transmitting over shorter distances
- mitigating PMD-induced distortions in the received electrical signal
- increasing the PMD tolerance through use of advanced FEC codes.

2.4.3.1 PMD Compensation Techniques

PMD is very difficult to compensate because the DGD and PSPs vary randomly with time and optical frequency. However, a number of PMD compensation techniques have been developed or proposed, which can be classified into three main categories:

- electrical PMD mitigation in direct detection receivers
- electrical PMD compensation in coherent receivers
- optical PMD compensation before the receiver.

In systems using non-coherent envelope detection, one may mitigate the PMD-induced distortions in the received electrical signal by employing adjustable transversal electrical filters (TEFs) or feed-forward equalizers (FFEs), nonlinear decision feedback equalizers (DFEs), or maximum-likelihood sequence estimators (MLSEs). These electrical equalizers, which are also used to mitigate other transmission impairments, are relatively inexpensive and robust, but their efficacy decreases rapidly when PMD becomes large.

Optical PMD compensators, on the other hand, are considered to be capable of mitigating large amounts of PMD. The block diagram of a typical optical PMD compensator is shown schematically in Figure 49. This compensator comprises an adjustable element for adaptive PMD compensation and an optical monitor to generate a feedback control signal for the compensator.

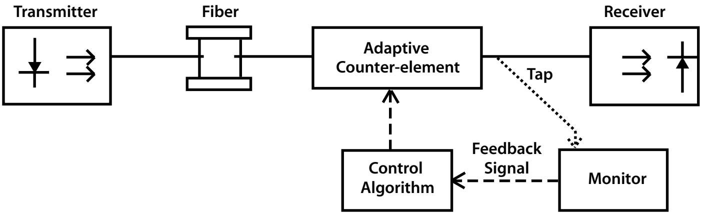


Figure 49: Schematic diagram of an optical PMD compensator

The adaptive compensation element usually comprises an adjustable polarization transformer and a tunable differential delay line to counteract the random variations in the DGD and PSPs of the fiber. However, reliable control of such compensators is a formidable task that has not yet been completely mastered.

Alternatively, one may compensate PMD in the electrical output signals of a coherent receiver with phase and polarization diversity. This solution should offer similar capabilities as optical PMD compensation and is substantially easier to implement.

2.5 Measuring Polarization Mode Dispersion

PMD is a major constraint in telecommunication transmissions over the fiber, so it is critical to characterize the fiber network in order to quantify the level of PMD and understand the fiber suitability to a given transmission rate.

2.5.1 When to Measure PMD

In general, PMD must be considered a potential issue in transmission systems that operate at bit rates higher than 2.5 Gbps. However, for certain fibers manufactured prior to 1996 or in analog transmission systems, PMD may become a limiting factor at substantially lower transmission speeds. The following list summarizes typical instances when PMD measurements may have to be performed:

- upgrading of existing networks to a bit rate of 10 Gbps
- upgrading of existing networks to a bit rate of 40 Gbps
- installing new ultra-long-haul networks operating at 40 Gbps or higher
- qualifying fiber during manufacturing
- qualifying fiber during or after cabling.

PMD is a statistical phenomenon, therefore, it may be necessary to repeat the PMD measurement at a later time to monitor long-term fluctuations of PMD.

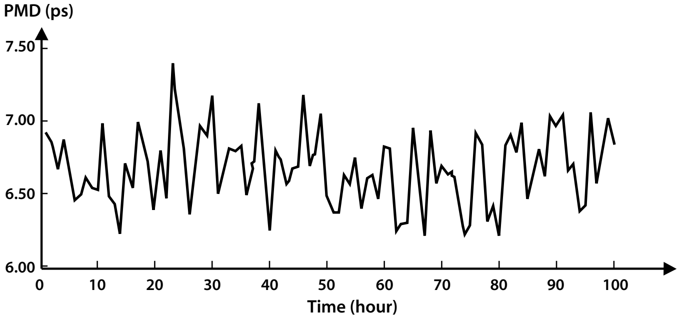


Figure 50: Long-term fluctuations of the average DGD

2.5.2 PMD Test Methods

As laid out in various test and measurement standards, several different methods exist for measuring PMD in deployed fibers. The four most common methods used are described below. Other methods are mainly dedicated to production/lab testing. These methods include Poincaré sphere measurements, modulation phase shift measurements, pulse or time delay measurements, and baseband curve fit methods.

The four methods described are classified following the IEC-60793-1-48 international standard. All test methods are also published in the ITU-T G650.2 standard. TIA provides a recommendation for each test solution. All four methods utilize the fact that the polarization transformation in PMD fibers is wavelength dependent, so that different frequency components are transformed into different polarization states at the output of the fiber. This wavelength dependence increases with increasing PMD and, hence, represents a unique measure of the average DGD $\langle \Delta\tau \rangle$ in the fiber.

Table 18: PMD standards and recommendations

Standards	Description
FOTP-113 TIA-455-113	PMD for single-mode optical fibers by the Fixed Analyzer method – Extrema counting (EC) – Fourier transform (FT)
FOTP-122 TIA-455-122A	PMD measurement for single-mode optical fibers by Stokes parameter measurements – Jones-matrix-Eigen analysis (JME) – Poincaré sphere analysis (PSA)
FOTP-124 TIA-455-124A	PMD measurement for single-mode optical fibers and cable assemblies by interferometry – Traditional interferometry (TINTY) – General interferometry (GINTY)
FOTP-196 TIA-455-196	Guideline for PMD and DGD measurement in single-mode fiber optic components and devices
IEC 60793-1-48	Measurement methods and test procedures—polarization mode dispersion – Fixed Analyzer measurement method (EC / FT) – Stokes evaluation method (JME / PSA) – Interferometry method (TINTY)
GR-2947-CORE	GR-2947-CORE refers to portable PMD test sets used for analyzing single-mode fiber
ITU-T G.650.2	Definitions and test methods for statistical and nonlinear attributes of single-mode fiber and cable – Stokes parameter evaluation technique (JME & PSA) – State of polarization method (SOP) – Interferometric methods (TINTY & GINTY) – Fixed Analyzer technique (EC / FT / cosine Fourier analysis)

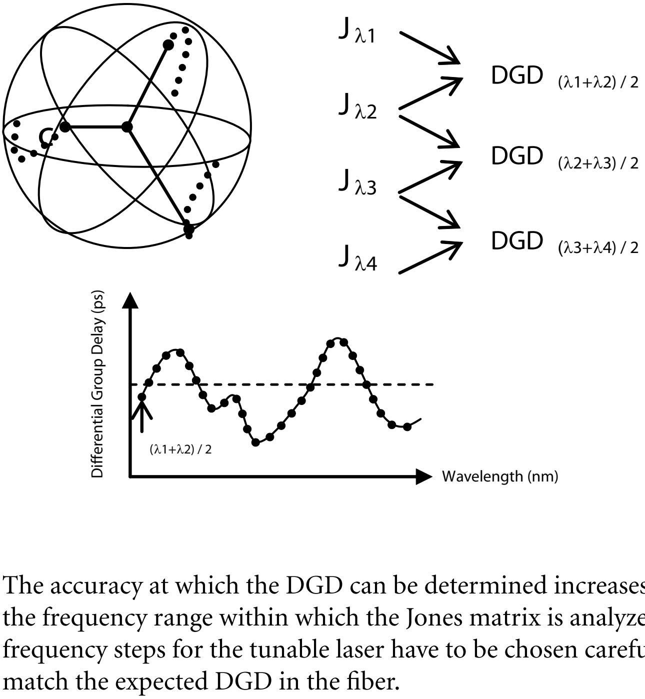
2.5.3 Jones-Matrix-Eigen Analysis

The Jones-Matrix-Eigen analysis (JME) is the ITU-T G.650.2 reference test method also described in the Stokes parameters evaluation technique. This test method is also standardized by the IEC 60793-1-48 and the TIA Fiber optic Test Procedure (FOTP)-122A measurement for single-mode optical fibers by Stokes parameter measurements.

2.5.3.1 Measurement Principle

The JME is a frequency polarimetric method that allows full PMD characterization by establishing the optical frequency dependence of the polarization dispersion vector. The magnitude of this vector is the differential group delay and its orientation yields the principal states of the fiber under test.

A tunable laser is stepped through a multitude of optical frequencies. At each of these frequencies, the polarization filter is adjusted to three different (and well defined) polarization states (linearly polarized 0°, 45°, and 90° or 0°, 60°, and 120°), and the three received polarization states are analyzed by the polarimeter. This information is sufficient to calculate the corresponding Jones matrix of the polarization transformation in the fiber. The wavelength dependence of these Jones matrices then yields the instantaneous DGD $\Delta\tau$ as a function of frequency and, consequently, the frequency averaged DGD $\langle\Delta\tau\rangle$.



The accuracy at which the DGD can be determined increases with the frequency range within which the Jones matrix is analyzed. The frequency steps for the tunable laser have to be chosen carefully to match the expected DGD in the fiber.

2.5.3.2 Test Equipment Setup

This method requires a narrowband tunable light source and an adjustable polarization filter at one end of the fiber and complete optical polarization analyzer (or polarimeter) at the other end of the fiber.

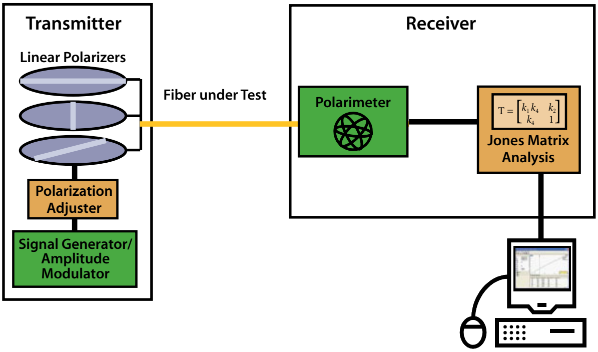


Figure 51: Typical schematic of the elements of the JME method

2.5.3.3 Typical Specifications and Measurement Ranges

The following is a list of typical specifications for a JME-based PMD analyzer.

Table 19: JME specification example

Min PMD	0 ps (typ.)
Max PMD	50 ps
Dynamic range	53 dB
DGD absolute uncertainty	50 fs
Measurement time	from 6 s

2.5.3.4 Benefits and Limits

The JME method provides a significant set of advantages, including:

- high dynamic range up to 50 dB (using a benchtop light source)
- good absolute uncertainty
- minimum DGD measurement range suitable for any fiber
- possible measurement through multiple EDFAs
- averaging unnecessary
- not sensitive to input polarization
- not sensitive to mode coupling
- second-order PMD measured directly.

But there are some drawbacks:

- expensive for a field solution
- one acquisition required for each wavelength
- laboratory solution, not field-proven or convenient (uses a benchtop light source)
- maximum PMD limited to 50 ps.

2.5.4 Fixed Analyzer Method

This method is standardized by the IEC 60793-1-48, the ITU-T G.650.2, and the TIA Fiber Optic Test Procedure (FOTP)-113 Polarization Mode Dispersion Measurement for Single-Mode Optical Fibers by the Fixed Analyzer Method.

2.5.4.1 Measurement Principle

The wavelength dependence of PMD in the fiber transforms the various wavelengths of the launched polarized light into different polarization states at the output of the fiber. As a result, the optical power after the polarization filter varies randomly with optical frequency. The mean DGD in the fiber can be calculated from the number of extrema, N_e, observed within a given frequency range as $\langle \Delta\tau \rangle = k_2 \ \pi N_e / \Delta\omega$, wherein $k_2 = 0.82$ for long fibers with strong mode coupling and $k_2 = 1$ for short fibers. Alternatively, one may Fourier transform the measured optical frequency spectrum into the time domain and fit the resulting data with a Gaussian function. The width of this curve is directly proportional to the root-mean-square DGD $\sqrt{\langle \Delta\tau^2 \rangle}$ that for long fibers with strong mode coupling is related to the average DGD as $\langle \Delta\tau \rangle^2 = 8/3\pi \langle \Delta\tau^2 \rangle$. The accuracy of this measurements increases with the optical bandwidth of the analyzed spectrum.

This Fourier analysis has the advantage of providing a graphical indication of the mode coupling characteristics of the sample. In addition, it allows filtering out high-frequency features (induced by noise or vibration) that would be detected as maxima and minima by the extrema-counting method.

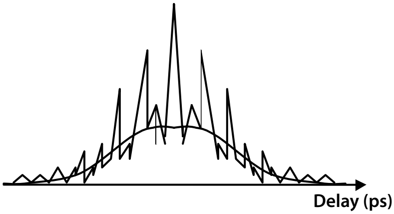


Figure 52: FFT graphical display for a random mode coupling

2.5.4.2 Test Equipment Setup

This method requires a polarized broadband light source at one end of the fiber and an analyzer (fixed optical polarization filter) followed by an optical spectrum analyzer (OSA) at the other end of the fiber.

The polarizer at the fiber input is needed only if the launch beam is not already polarized (usually a 3 dB extinction ratio is sufficient). The angular orientation of the polarizers is not critical, but should remain fixed throughout the measurement.

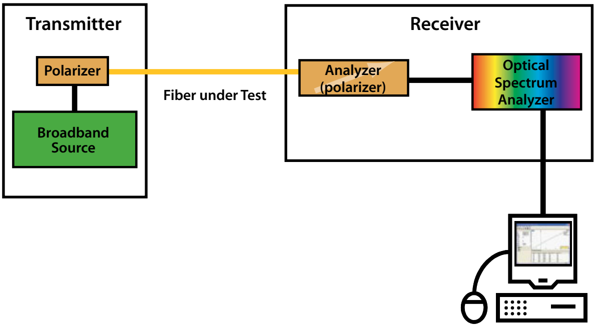


Figure 53: Typical schematic of the elements of the Fixed Analyzer method

2.5.4.3 JDSU Fixed Analyzer Test Method

JDSU has developed a solution based on the Fixed Analyzer method that allows very fast acquisition time and analysis over a wide wavelength in a compact and rugged form factor. This permits the offering of the highest performance dedicated test solution for the field application.

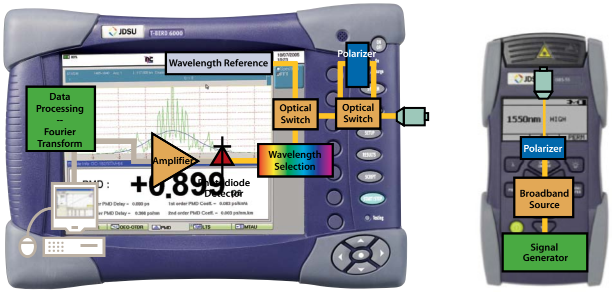


Figure 54: JDSU Fixed Analyzer PMD module and the T-BERD/MTS-6000 platform

2.5.4.4 Typical Specifications and Measurement Ranges

The following is a list of typical specifications for an FA (FT)-based PMD analyzer.

Table 20: FA (FT) specification example

Minimum PMD	0.08 ps
Maximum PMD	130 ps
Dynamic range	65 dB
PMD absolute uncertainty	± 0.02 ps ± 2% PMD
Repeatability	±0.025 ps
Measurement time	from 6 s

2.5.4.5 Benefits and Limits

The Fixed Analyzer method provides a significant set of advantages, including:

- high dynamic range: >55 dB using a handheld light source
- good absolute uncertainty
- minimum DGD measurement range suitable for any fiber
- possible measuring through multiple EDFAs
- fast measurement (from 6 s)
- robust and field-dedicated instrument with no moving parts (Fabry-Perot filter technology); limits risk of failure; small and light
- Very easy to use; no specific parameter settings necessary.

Limitations of the Fixed Analyzer method include:

- averaging might be necessary depending on fiber loss
- second-order PMD not measured directly, but calculated
- possible limitation with very high PMD values, however suitable for any telecom fiber
- sensitive to input polarization.

2.5.5 Interferometry: Traditional Method (TINTY)

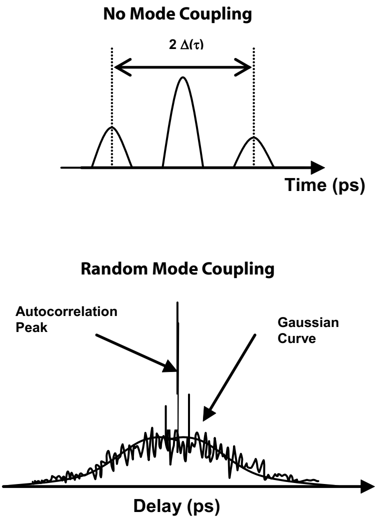
This method is standardized by the IEC 60793-1-48, the ITU-T G.650.2, and the TIA Fiber Optic test Procedure (FOTP)-124A Polarization Mode Dispersion Measurement for Single-Mode Optical Fibers and Cable Assemblies by Interferometry.

2.5.5.1 Measurement Principle

The Interferometric method relies on the measurement of the mutual coherence (electric field auto-correlation) between different polarizations at the fiber output. A polarized broadband light source is injected into the fiber under test (FUT). Then, the light passes a Michelson interferometer where it is split into two beams along the interferometer arms with each beam representing one orthogonally polarized state to the other. One arm is directed at a fixed mirror, introducing a fixed time delay, and the other arm is directed at a moving mirror, introducing a variable time delay. Then the beams are recombined before being focused onto a detector. Interference fringes (amplitude maxima and minima) are measured by moving the variable mirror. The resulting interferogram obtained represents the cross-correlation function.

For fiber links (usually exhibiting 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. The central peak of the interferogram corresponds to the mirror position where both interferometer arms are of equal length. The peak obtained through this analysis is the auto-correlation function and is actually the Fourier transform of the light source spectrum.

The fringe envelopes obtained from this method are a combination of the cross-correlation and autocorrelation functions. An algorithm is used to remove the central autocorrelation peak, which contains no PMD information; the PMD value at this point is then estimated.



$\Delta\tau = (2. \Delta x / c)$

Where
$\Delta\tau$ is the PMD delay
Δx is the moving path of the optical delay line
c is the light velocity in the vacuum

$\Delta\tau = \sqrt{(3/4)}\,\sigma$

Where
$\Delta\tau$ is the PMD delay
σ is the standard deviation of the Gaussian curve

Figure 55: Interferometry response according to type of mode coupling

2.5.5.2 Test Equipment Setup

This method requires a polarized broadband light source at one end of the fiber and a tunable Mach-Zehnder or Michelson interferometer at the other end.

The analyzer polarizes the light over the full wavelength range of the source.

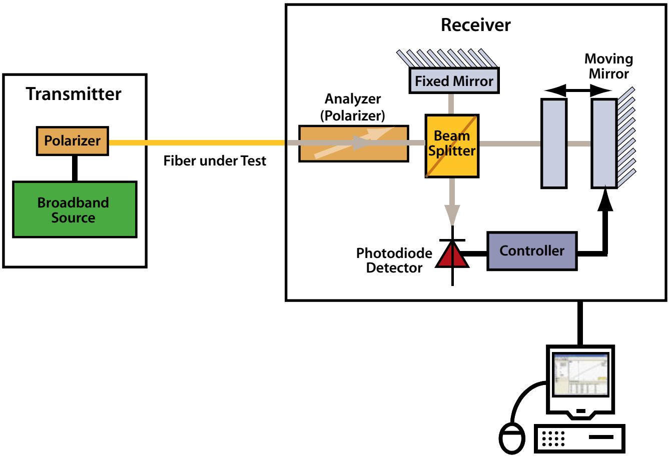


Figure 56: Typical schematic of the elements of the TINTY method

2.5.5.3 Benefits and Limits

The Interferometric method provides three advantages:

- high dynamic range (up to 64 dB using a benchtop light source)
- good absolute uncertainty (but includes a systematic error due to the interferogram central peak removal)
- minimum DGD measurement range suitable for any fiber.

Disadvantages of the Interferometric method include:

- not field rugged, risk of failure due to moving parts
- long measurement time; averaging necessary
- not easy to use; the correct DGD range must be set before testing
- second-order PMD not measured directly, but calculated
- sensitive to input polarization.

2.5.5.4 Typical Specifications and Measurement Ranges

The following is a list of typical specifications for a TINTY-based PMD analyzer.

Table 21: TINTY specification example

Minimum PMD	0.035 ps
Maximum PMD	80 ps
Dynamic range	64 dB
PMD absolute uncertainty	1% ± 0.06 ps (weak mode coupling)
Repeatability	1% ± 0.06 ps (strong mode coupling)
Measurement time	8 to 15 s depending on delay values

2.5.6 Interferometry: Generalized Method (GINTY)

The GINTY method is standardized by the IEC 60793-1-48, the ITU-T G.650.2, and the TIA Fiber Optic test Procedure (FOTP)-124A Polarization Mode Dispersion Measurement for Single-Mode Optical Fibers and Cable Assemblies by Interferometry.

2.5.6.1 Measurement Principle

The principle of the GINTY method is the same as the TINTY method but with a modified setup. The differences are as follows.

The polarization beam splitter allows simultaneous detection of each orthogonal mode. Although, with the TINTY method the auto- and cross-correlation interferograms are measured separately via the sum and difference of two interferograms observed along orthogonal polarization axes.

The analyzer must be capable of being rotated to a setting orthogonal to the initial setting.

The polarization scramblers, which are not explicitly part of the GINTY method, enable selecting input and output states of polarization for the fiber under test. Using these devices, the PMD is deduced from the mean square envelope of the interferograms rather than from the average of the individual estimates deduced from individual squared envelopes observed at various scrambler settings.

2.5.6.2 Test Equipment Setup

This method is similar to the above described TINTY method but requires an additional polarization scrambler at both ends of the fiber.

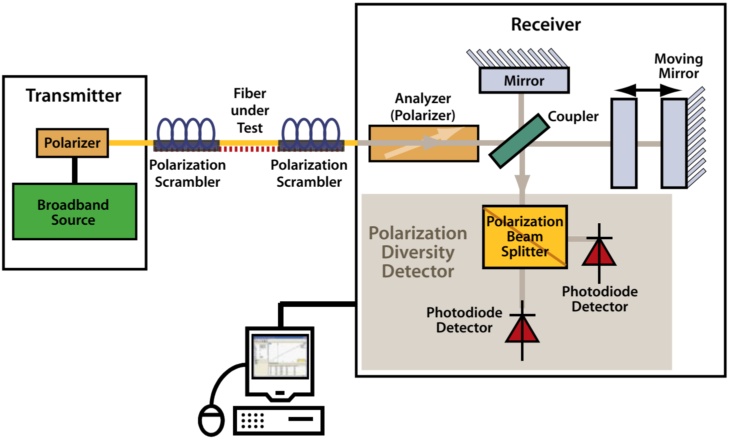


Figure 57: Typical schematic of the elements of the GINTY

2.5.6.3 Typical Specifications and Measurement Ranges

The following is a list of typical specifications for a GINTY-based PMD analyzer.

Table 22: GINTY specification example

Measurement range	0 – 115 ps
Dynamic range	30 dB with handheld source 47 dB with lab type source
PMD absolute uncertainty	± (0.02 + 2% of PMD)
Measurement time	4.5 s

2.5.7 Benefits and Limitations

This measurement method, derived from the TINTY method, presents some significant advantages and improves the TINTY measurement method as follows:

- dynamic range: up to 47 dB (using a benchtop light source)
- good absolute uncertainty
- minimum DGD measurement range suitable for any fiber
- possible to measure through multiple EDFAs
- very fast measurement (from 5 s)
- not sensitive to input polarization when using polarization scramblers.

It did not get rid of all the TINTY disadvantages:

- not shock proof, risk of failure due to moving parts
- polarization scramblers required to get full benefit of this method
- limited dynamic range with a portable light source
- second-order PMD not measured directly, but calculated
- sensitive to input polarization when no polarization scramblers are in place.

2.5.8 Measurement Applications

Despite the performance differences between each measurement method, there are limitations to consider when choosing a PMD analyzer.

Table 23: PMD measurement method application

Applications	JME	FA (FT)	TINTY	GINTY
Fiber and cable manufacturing	✓	✓	✓	✓
Non-amplified links (outside plant tests)				
– Metro networks (<30 dB)	✗[1]	✓	✓	✓
– Long haul networks (>30 dB)	✗[1]	✓	✓	✗[2]
Non-amplified links (inside plant tests)	✓	✓	✓	✓
Amplified links	✓	✓	✓	✓
Aerial links	✓	✓	✓	✓
Submarine links	✓	✓	✓	✓

1. Battery-operated and field-rugged light source not available.
2. Limited dynamic range with a battery-operated light source.

2.5.9 Measurement Method Comparison

Various side-by-side evaluations have been conducted by standardizing bodies in order to understand what could be expected when comparing test results from methods. Extracts of their conclusions are reported below:

1. "With PMD … there exists more than one viable technique by which the measurement can be performed … Due to the complex nature of PMD in standard telecommunications-grade fiber, many subtleties exist … that are not fully understood."

2. "Inter-laboratory measurement comparisons indicate that systematic and random disagreements of ±10 to ±20% between measurement methods and calculations are common … at the present time … agreement of ±10 to ±20% is considered to be *state of the art*".

Interferometry and Fourier-transformed fixed analyzer [methods] point to "pulse spreading" of the PMD and "J-M Eigen analysis and cycle-counted fixed analyzer [methods] point to the" DGD of the PMD.

Here it is significant to note that TIA points out the potential for significant systematic disagreement between the JME method and the Interferometric method for the reasons mentioned above.

However, the Fixed Analyzer test method has the ability to analyze the data using Fourier transformations, thereby maximizing its potential repeatability with the results of either alternate method.

The TIA recommendation specifically states, "Extensive simulation and measurement experience shows fairly good statistical agreement between Fixed Analyzer and J-M Eigen analysis."

It also further states, “It is widely agreed that … responses produced by Interferometry and Fourier transformed fixed analyzer [methods] should be equivalent and that there should be good statistical agreement among them.”

2.5.9.1 FA and JME Comparison

Inter-comparison measurements have been conducted with various test methods and present good agreement with laboratory implementations of the JME method from two different vendors. The test shown in Figure 58 compares the mean value of 20 successive measurements with random input and output polarization states compared with single measurements of the JME. Both real fibers and PMD artifacts were used in those measurements.

Those results show that there is very good correlation between the FA and the JME measurements.

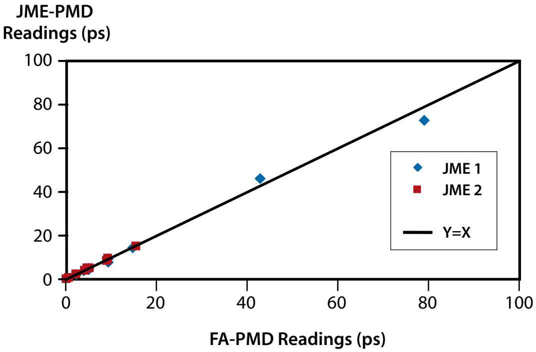


Figure 58: JME and FA comparison graph

2.5.9.2 TINTY and FA Comparison

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

Table 24: PMD measurements showing the differences between the TINTY and Fixed Analyzer test methods

	Distance (km)	TINTY Method (ps)	Fixed-Analyzer Test Method (ps)	Difference (%)
New fiber measurements (on drums)	100	0.77	0.85	10
New deployed fiber measurements (>2000)	69	0.282	0.282	1
	89	0.519	0.479	8
Old fiber measurements (<1993)	16	7.26	6.16	16
	32	8.37	7.0	16

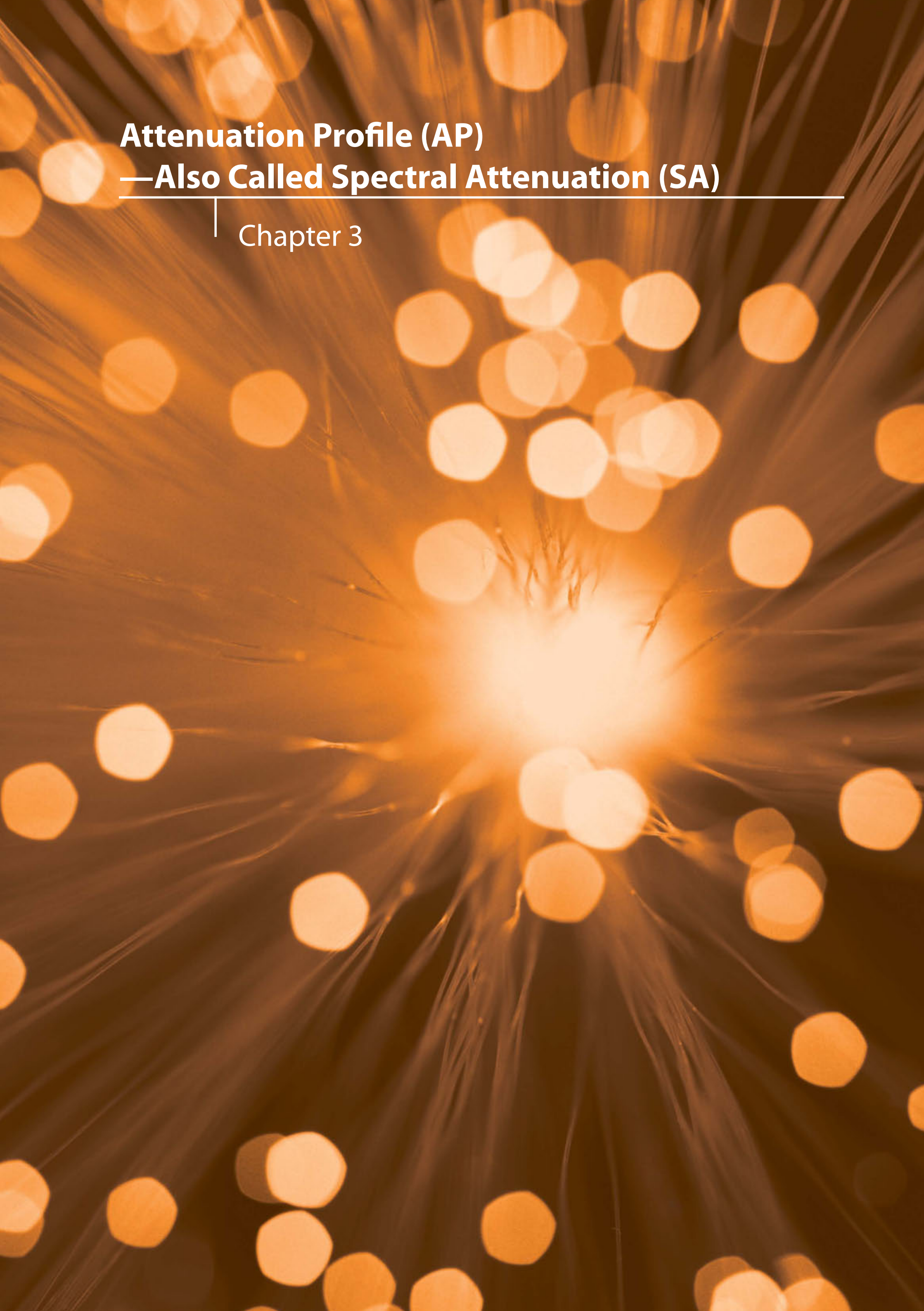
This data confirms that the differences between the Interferometry (TINTY) and Fixed Analyzer methods published by TIA are in the range of 10 to 20%. Furthermore, repeat measurements show results variation with both methods due to the statistical changes of PMD values.

2.5.10 Conclusion

PMD in optical fibers is becoming an important issue as data rates increase to 40 Gbps and beyond. Unlike with CD, no simple, cost-effective solutions exist for adaptive compensation of high amounts of first- and higher-order PMD. High PMD, therefore, has become the biggest obstacle in upgrading existing networks to higher bit rates. Any decision on whether to upgrade a certain link to higher transmission speeds requires precise knowledge of the average DGD in the link that can only be obtained by measurement.

Attenuation Profile (AP) —Also Called Spectral Attenuation (SA)

Chapter 3



3.1 Introduction

In fiber optic transmission, several wavelength regions, called windows, are utilized with different windows typically used in different applications. These windows are generally centered about 850, 1310, and 1550 nm. Each of these windows was historically selected due to a technological or performance advantage such as available lasers (850 nm), low chromatic dispersion (1310 nm), or low attenuation (1550 nm). Initially, only a single wavelength channel was used per wavelength window; however, the dense wavelength division multiplexing (DWDM) transmission technology introduced the concept of packing multiple independent wavelength channels into the 1550 nm window. This window (approximately 1530 – 1565 nm) is commonly referred to as the “C-band.” To further increase capacity, a second DWDM window from 1565 – 1625 nm has been employed commonly referred to as the L-band.

Table 25 shows the allocation of spectral bands for single-mode fiber systems.

Table 25: DWDM Wavelength Bands

Wavelength Band	Wavelength Range
O-band	1260 – 1360 nm
E-band	1360 – 1460 nm
S-band	1460 – 1530 nm
C-band	1530 – 1565 nm
L-band	1565 – 1625 nm
U-band	1625 – 1675 nm

To enable lower-cost transceivers, coarse wave division multiplexing (CWDM) technology utilizes uncooled semiconductor technology requiring adjacent channels to be spaced by 20 nm. CWDM channels cover the entire single-mode transmission band from 1261 to 1621 nm (defined by ITU-T G.695). Within this wavelength band, some types of fibers possess regions of high optical loss centered about 1383 nm (commonly referred to as the “water-peak”), which

limits the suitability of these types of fibers to the use of a subset of CWDM channels.
In long-distance transmission, as well as at a very high bit rate (10, 40, and 100G systems), some systems employ Raman amplification to compensate for the loss in the fiber. In addition, distal pumping of Erbium amplifiers using 1480 nm is currently deployed. These applications require characterization of the fiber loss at the pump wavelengths (such as 1420, 1450, and 1480 nm) to ensure the proper amount of amplification will occur.

As all of these applications make such a broad and varied use of the spectrum of the optical fiber, characterization of the optical loss over the full useful wavelength region is required and characterizing the loss at only a single discrete wavelength is not always sufficient.

3.2 Fiber Attenuation vs. Wavelength

The attenuation of optical fiber changes with wavelength and with the general fiber design or fiber type. The main contribution and ultimate limitation to fiber losses is due to Rayleigh scattering, with the loss being inversely proportional to the fourth power of the wavelength. By plotting the attenuation of a fiber versus wavelength, some characteristics of the fiber can be identified. The graph of Figure 59 illustrates an example of the loss versus the wavelength of a typical fiber.

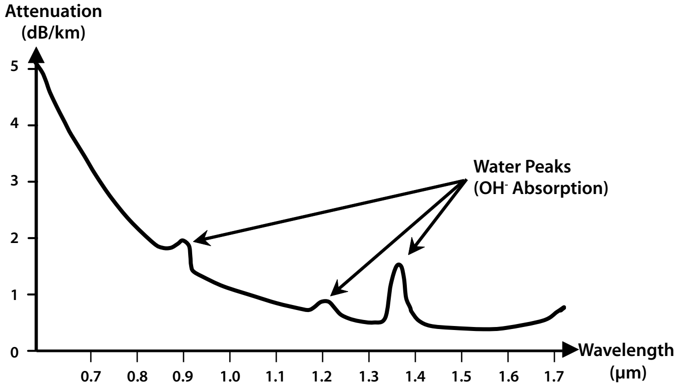


Figure 59: Fiber attenuation as a function of wavelength

The main telecommunication transmission wavelength windows are located at regions where attenuation is at the lowest levels.

At around the wavelengths of 950, 1244, and 1383 nm, the presence of hydrogen and hydroxide ions (OH^-) within the fiber material causes an increase in attenuation ("water peaks"). These ions result from traces of water entering the fiber material during the manufacturing process. Two wavelengths fall into the telecommunications wavelength windows; one is at 1244 nm and the other is at 1383 nm. The absorption attributed to the water peak at 1240 nm (in dB/km) is always higher that at 1383 nm.

The attenuation above is intrinsic to the fiber design and manufacture. It is also important to verify fiber attenuation after fiber installation to measure attenuation due to bending loss. Fiber bending loss is generally highly wavelength dependent. Small bends in the fiber created by uneven pressures placed on the fiber generate an increase of loss that increases with wavelength. The dependence with wavelength is roughly exponential but periodic oscillations are also superimposed, which results in a complex dependence with wavelength.

3.3 Low Water Peak Fibers

Recent advances in the manufacturing processes of optical fiber have significantly reduced the 1383 nm water peak attenuation and resulted in “low water peak” fibers. Examples of this type of fiber include SMF-28e™ from Corning and AllWave™ from OFS.

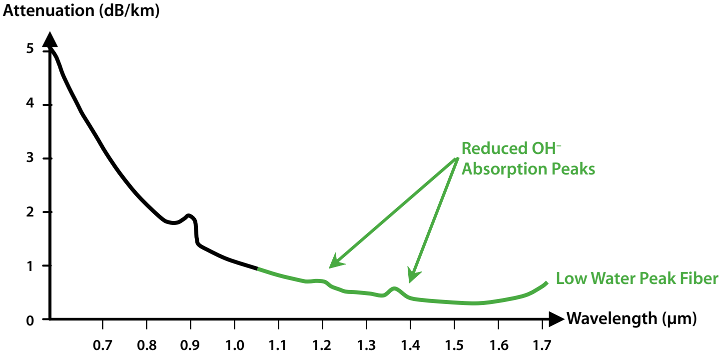


Figure 60: Fiber attenuation as a function of wavelength

3.4 Different Types of Single-Mode Fiber

The International Telecommunication Union (ITU-T) has taken the attenuation factor into account to classify single-mode fibers according to their suitability to given transmission applications. The table below shows four of the sub-classifications of G.652 fiber, based on fiber attenuation over various wavelength ranges.

Table 26: G.652: Characteristics of single-mode optical fiber and cable

	Characteristics	Wavelength Coverage	Applications
G.652.A		1310 and 1550 nm regions (O- and C-bands)	Supports applications such as those recommended in G.957 and G.691 up to STM-16, 10 Gb/s up to 40 km (Ethernet), and STM-256 for G.693.
G.652.B	Maximum attenuation specified at 1625 nm.	1310, 1550, and 1625 nm regions (O- and C+L-bands)	Supports some higher bit rate applications up to STM-64 in G.691 and G.692 and some STM-256 applications in G.693 and G.959.1. Depending on the application, chromatic dispersion accommodation may be necessary.
G.652.C	Maximum attenuation specified at 1383 nm (equal or lower than 1310 nm).	From O- to C-bands	Similar to G.652.A, but this standard allows for transmission in portions of an extended wavelength range from 1360 to 1530 nm. Suitable for CWDM systems.
G.652.D	Maximum attenuation specified from 1310 to 1625 nm. Maximum attenuation specified at 1383 nm (equal or lower than 1310 nm).	Wideband coverage (from O- to L-bands)	Similar to G.652.B, but this standard allows for transmission in portions of an extended wavelength range from 1360 to 1530 nm. Suitable for CWDM systems.

3.5 Fiber Suitable for Extended DWDM and CWDM Transmission Systems

Is my fiber network compatible with CWDM deployment in the full wavelength range? It’s a question that network planners and engineers should consider when they begin thinking of bringing new technologies in order to increase the bandwidth capacity of their network and deliver more services to their customers.

More recently, fibers have been developed to comply with the dedicated ITU-T subcategories to overcome the high attenuation water peak around 1383 nm. Meanwhile, this issue still remains an important consideration regarding extending the usable spectrum of your existing fiber plant. In fact, it is most often the case that no AP documentation records exist for this particular parameter for older fiber plant.

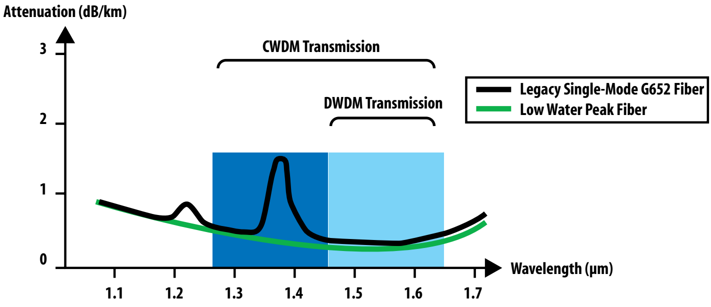


Figure 61: Fiber attenuation as a function of wavelength related to CWDM and DWDM transmissions

To illustrate, Figure 62 provides two measurements of the attenuation around 1383 nm of two different fibers. One is an older fiber possessing a typical water peak and the other is a “low water peak” fiber designed to have a significantly improved attenuation in this region.

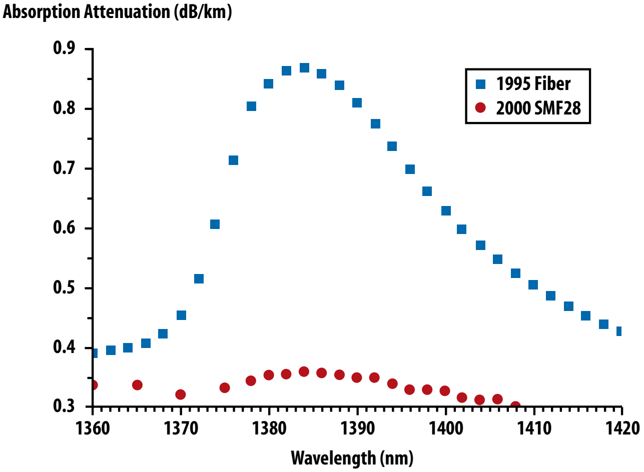


Figure 62: OH– absorption vs. fiber manufacturing time

The knowledge of the fiber attenuation at this 1383 nm area allows the operator to determine the compatibility with CWDM and extended DWDM transmission systems.

3.6 Attenuation Profile Measurement Requirements

The purpose of the AP measurement is to characterize and measure the attenuation as a function of wavelength.

On most systems operating today, attenuation measurements have only been performed at select points. However, with the increase of CWDM deployments and the extension of the DWDM wavelength range, it is becoming necessary to have a clear picture of the fiber attenuation profile to evaluate a fiber's suitability for these applications.

3.6.1 Test Methods

Different methods are used to measure attenuation profile:

- Use of a broadband source and an optical spectrum analyzer (OSA). Both have a wavelength range equal to or larger than the transmission band.
- Use of a multi-wavelength or tunable light source and a broadband power meter.
- Use of a multi-wavelength OTDR.

In addition to the ITU-T G.65x fiber specifications, the standardization bodies provide some guidance about spectral attenuation measurements.

Table 27: Guidance about spectral attenuation measurement

Standards	Description	Limits
ITU-T G.692 Chapter 6.4.1	Optical interfaces for multichannel systems with optical amplifiers	Typical 0.28 dB/km between 1530 – 1565 nm
TIA/EIA-455-61	Measurement of fiber or cable attenuation	0.25 dB/km at 1550 nm 0.25 dB/km at 1600 nm
IEC 61300-3-7	Fiber optic interconnecting devices and passive components—Basic test and measurement procedures—Part 3-7: Examinations and measurements—Wavelength dependence of attenuation and return loss	

As attenuation profile measurement is highly recommended before DWDM/CWDM installations, the use of an OSA provides the best solution in order to characterize the fiber as well as to perform system verification testing.

3.6.2 Characterizing Attenuation vs. Wavelength, Including the OH– Absorption Peak with an Optical Spectrum Analyzer

If the C-band is used for DWDM transmission, then the spectral attenuation shall be made in the C-band. However, for future considerations, spectral attenuation can easily be made over a broader wavelength range. It is recommended to perform the analysis over at least the C+L band (1530 to 1610 nm). When CWDM transmission is involved, then the full band (1261 to 1621 nm) must be characterized.

Using a broadband source/OSA combination, the procedure is as follows:

1. Directly connect the broadband source and the OSA through a jumper to obtain a power level versus wavelength reference. This allows any structure to be normalized in the emitted power versus wavelength of the broadband source, as well as the loss of the fiber jumper.
2. Connect the broadband source and the OSA to either end of the fiber.
3. Measure the attenuation and the optical power versus wavelength after the signal has propagated through the fiber. Subtract the reference power versus wavelength measurement data (in logarithmic units) from this to obtain the attenuation profile of the fiber.
4. Determine power losses according to the wavelength by comparing them to a reference spectrum.

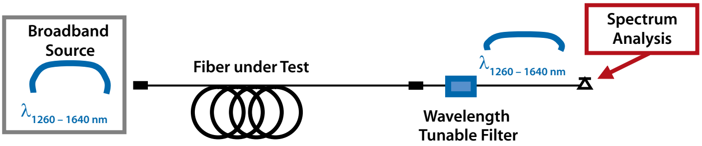


Figure 63: Test setup of attenuation profile measurement using an optical spectrum analyzer

To convert the attenuation profile to a level normalized to distance (attenuation given in dB/km), divide the total loss at each wavelength by the total fiber length.

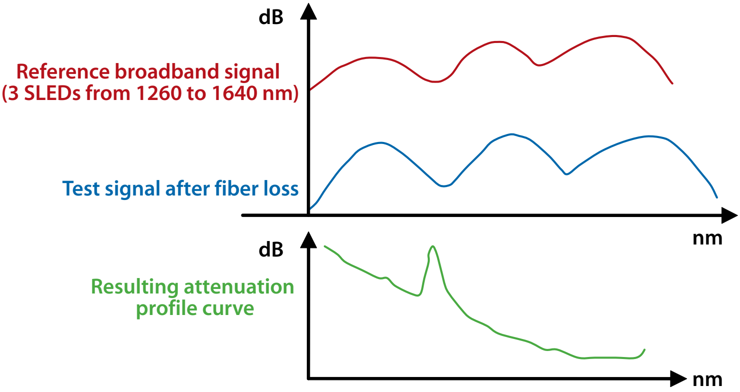
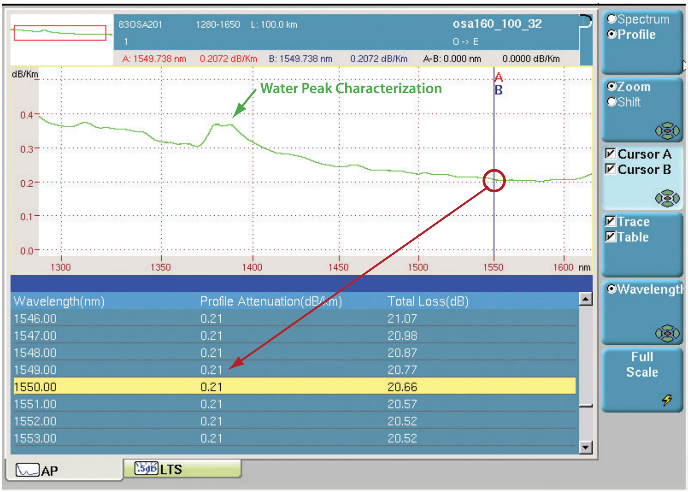


Figure 64: Broadband source spectrum comparison resulting to attenuation profile

Typically, spectral attenuation measurements are performed in one direction.

In order to address both DWDM and CWDM applications, JDSU provides different solutions, using either the T-BERD/MTS-8000 or T-BERD/MTS-6000 platforms.

Whatever the broadband source wavelength range, the solutions can immediately provide the attenuation of the fiber at a given wavelength range.



A: 1549.738 nm 0.2072 dB/Km B: 1549.738 nm 0.2072 dB/Km A-B: 0.000 nm 0.0000 dB/Km

Wavelength(nm)	Profile Attenuation(dB/km)	Total Loss(dB)
1546.00	0.21	21.07
1547.00	0.21	20.98
1548.00	0.21	20.87
1549.00	0.21	20.77
1550.00	0.21	20.66
1551.00	0.21	20.57
1552.00	0.21	20.52
1553.00	0.21	20.52

Figure 65: Measuring the attenuation profile with the T-BERD/MTS-8000

3.7 Conclusion

As wavelength ranges used for transmission broaden and become more diverse and as different fiber types grow more numerous, it is critical to accurately characterize the attenuation profile of the fibers intended to be used. JDSU provides innovative solutions for the field technicians to complete the job with the right performance in the right form factor.

Fiber Link and Network Characterization

Chapter 4

4.1 Defining Fiber Link Characterization

Today's fiber networks have to meet exacting performance requirements to withstand the demands of widespread broadband access technology deployment. In addition to deploying fiber infrastructures that perform perfectly, network operators are challenged by the need to reduce operating expenses while adding new revenue-generating services, all within an environment that seems to grow more complex by the minute.

At the test level, the growing demand for 10 GigE and 10 Gbps SONET/SDH systems, as well as the emergence of 40 and 100 Gbps, requires that more and more fiber links be fully characterized. Adding to the complexity of testing these networks is the type of transmission and associated bit rate as well as equipment manufacturer specifications, both of which dictate the type of tests to perform and the measurement limits to consider.

Fiber link characterization is not simply one test function. Rather, it is a comprehensive suite of point-to-point physical layer (including components) optical tests measuring and determining the quality and potential transmission capability of a given optical fiber. Fiber link characterization includes the tests shown in Table 28 and requires the associated tools.

If one or more of these measurements is not in accordance with defined thresholds (either provided by international standards or by operators/equipment manufacturers), then the network will not work properly or will not be upgradeable to higher bit-rate transmission levels.

Table 28: Summary of link characterization tests

Test Parameters	Measurement Tool
Connector inspection	Video inspection scope
Insertion loss measurement	Light source/power meter
Distance measurement (fiber length)	OTDR
Connectors/splice measurements	OTDR
Reflectance measurements	OTDR
ORL measurements	ORL meter or OTDR
PMD measurements	PMD analyzer
CD measurement	CD analyzer
AP measurements	Spectral analyzer

4.2 When Characterizing a Fiber Link

Link characterization measurements are performed during all phases of the network life cycle:

- at first fiber installation
- for final commissioning and acceptance
- during fiber and system upgrade
- after fixing break, for troubleshooting and maintenance.

Although a complete fiber link characterization suite includes the measurements listed above, the test scenarios can vary from one operator to another. The primary considerations in defining a test scenario is the type of transmission planned for the link and what is known about the condition of the link already such as its age and current performance. For example, it could consist only of optical time domain reflectometry (OTDR), chromatic dispersion (CD), and polarization mode dispersion (PMD) testing.

When tests are complete, all data is collected and reported for final acceptance, then archived in a database that can be updated as necessary.

Table 29: Dispersion thresholds according to the transmission rate for NRZ coding format

Bit Rate Per Channel	Type of Transmission	PMD Delay Limit (ps)	Maximum CD at 1550 nm (ps)
2.5 Gbps	OC-48/STM-16	40	18817
10 Gbps	OC-192/STM-64	10	1176
40 Gbps	OC-768/STM-256	2.5	73.5
10 Gbps	Ethernet	5	738

Table 30: Link characterization test requirement summary

Test	2.5 Gbps STM-16/ OC-48 1550	2.5 Gbps STM-16/ OC-48 DWDM	10 Gbps STM-64/ OC-192 1550	10 Gbps STM-64/ OC-192 DWDM	40 Gbps STM-256/ OC-768 DWDM	10 Gb/s Ethernet	Equipment Required	Testing Recommended
Insertion loss	1310/ 1550 nm	1550/ 1625 nm	1310/ 1550 nm	1550/ 1625 nm	1310/1550/ 1625 nm	1310/ 1550 nm	PM & LS, or LTS	Unidirectional
Return loss	1550 nm	1550 nm	1550 nm	1550 nm	1550 nm	1550 nm	OTDR or ORL Meter	Unidirectional
Physical plant verification (incl. connector/ splices/ distance)	1310/ 1550 nm	1550/ 1625 nm	1310/ 1550 nm	1550/ 1625 nm	1310/ 1550 nm	1310/ 1550 nm	2 or 3 wavelengths OTDR	Bidirectional
PMD	<80 km not required unless pre-1993 fiber	<80 km not required unless pre-1993 fiber	Required	Required	Required	Required	BB Source, PMD Analyzer	Unidirectional
Chromatic dispersion	Not required if less than 150 km	Not required if less than 150 km	Recommended	Recommended	Recommended	Recommended	4 Lambda OTDR or Phase Shift Analyzer	Unidirectional
Attenuation profile	No	1550 – 1625 nm	No	1550 – 1625 nm	1550 – 1625 nm	1550 – 1625 nm	BB Source and OSA	Unidirectional

Note: This table is greatly simplified and each user must review and modify it in accordance with their specific network element equipment and application.

4.3 Defining Network Characterization

Network characterization is distinguished from fiber link characterization as it is performed after network elements implementation, including dispersion compensating modules and optical amplifiers, just prior to turn-up. It provides a baseline of the network architecture and the expected network performance. This is an end-to-end measurement requiring tests of only the CD, PMD, and attenuation profile (AP).

- The CD measurement confirms that the correct amount of compensation has been implemented.
- The PMD measurement verifies that the insertion of network elements has not contributed excessive additional PMD.
- The AP testing confirms the proper location and configuration of optical amplifiers and verifies loss characteristics contributed by other Network Elements (such as DCMs) at each operating wavelength of the network.

Network characterization requires the use of measurement methods suitable for testing through the different elements such as amplifiers and dispersion compensators. As noted, while several approved and standardized test methods exist, not all can measure through amplifiers or DCMs.

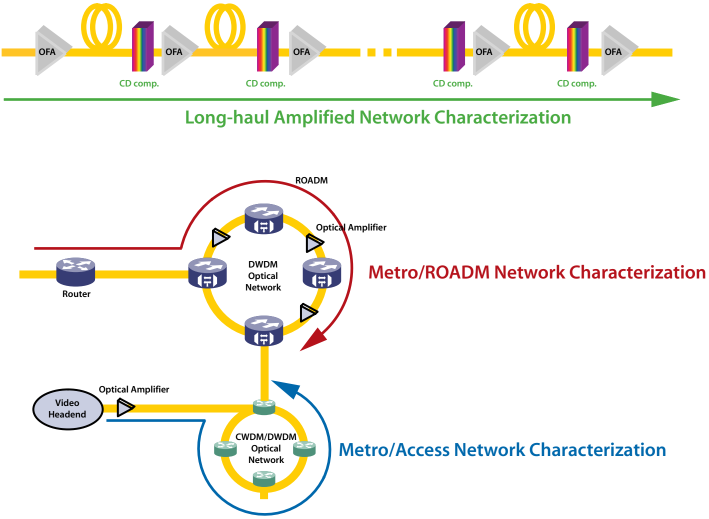


Figure 66: Example of route of tests for network characterization

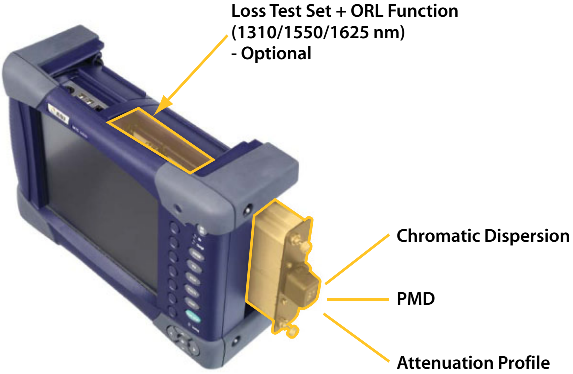


Figure 67: JDSU network characterization solution with T-BERD/MTS-6000A and ODM module

4.4 Field-Optimized Test Solutions

To carry out complete fiber link and network characterization, field technicians need the right tools.

For very long haul or submarine network characterizations, technicians traditionally carry a number of specialized testers. For complex networks (such as metro networks) it is necessary to perform the same suite of tests but on a far greater number of fibers. The ideal field solution combines all test equipment in one product (a test "platform") that is battery operated, portable, lightweight, and shock-proof. Complementary test equipment (such as a light source or broadband source) must also be battery operated, portable, and rugged.

The JDSU T-BERD/MTS-8000 allows combining all required tests in one unit with dedicated plug-in modules for insertion loss and ORL (bidirectional test), OTDR, and CD/PMD/AP and associated accessories such as video inspection scope and portable broadband source.

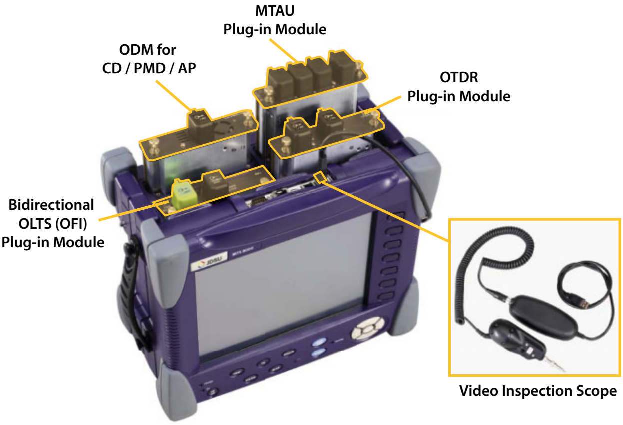
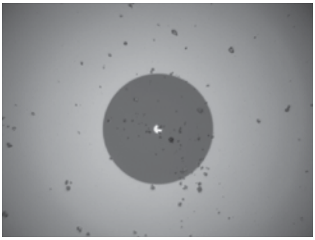


Figure 68: JDSU T-BERD/MTS-8000 with its plug-in modules and accessories for fiber characterization

4.4.1 Inspect Before You Connect!

A major problem that occurs during link characterization measurements is caused with the fiber connectors themselves and the simple act of connecting and disconnecting them. All connectors must be properly cleaned before use and cleanliness has to be verified. Connectors are the only elements that can be easily disconnected and are subjected to dirt or scratches prior to reconnection. File studies have shown that dirty or damaged connectors generate up to 80 percent of link/system failures.



Dirt is EVERYWHERE!

Air, hands, bulkhead adapter, dust caps, and elsewhere.

Dirt damages fiber!

Mating dirty connectors embeds debris into the glass.

Figure 69: Connector image with pits of dirt

- Contamination is the number one source of outages and required troubleshooting in optical networks.
- An average dust particle is 2 – 5 µm. A single particle mated into the 9 µm core of a single-mode fiber can cause significant back reflection, signal loss, and even equipment damage.
- Even new connectors are not always clean. Dust caps protect the fiber end face, but are often a source of contamination themselves.

Inspection and cleaning procedures consist of verifying the connector surfaces (both sides of the connector), using a video inspection scope, and cleaning the connectors with appropriate cleaning tools.

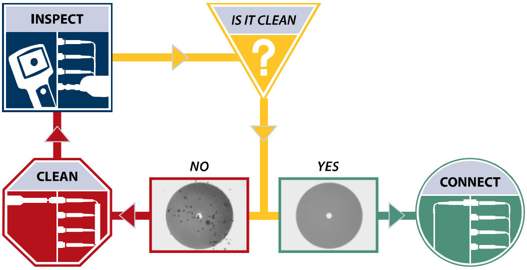


Figure 70: Connector inspection and cleaning steps

4.4.1.1 Inspect Both Sides of the Connector

It is important to inspect both sides of the connector of a patch panel. Patch cords are easy to access, whereas the bulkheads are often overlooked. The bulkhead side is half of the connection, but is far more likely to be dirty.

Inspecting both sides (male and female) of a fiber interconnect is the only way to ensure that the mated connection will be free of contamination.

Figure 71: Patch cord inspection

Figure 72: Bulkhead inspection

4.4.1.2 Fiber Inspection Test Solutions

The test equipment must give the technician the ability to inspect the connector surface. Advanced test platforms that support video inspection scope plug-in and operation also deliver the functionality to display the connector image. It is also imperative to perform an on-line comparison during the cleaning process (before and after).

Figure 73: JDSU T-BERD/MTS-8000 platform and video scope combination

4.4.2 Insertion Loss Measurements

The insertion loss (IL) measurement is the most important test to perform, as each combination of transmitter/receiver has a power range limit. If this limit is reached, the signal could not be transmitted or will be received with too much noise.

The measurement of the insertion loss of a signal over a complete link requires a calibrated source and a power meter. The source sends a signal at a given power level, and the power meter reads the remaining power level at the far end of the link.

An IL measurement is a two-step operation:

- The first step, called reference power measurement, is performed at the beginning of the measurement campaign or each time the jumper is disconnected from the source. The purpose of the reference power measurement is to quantify the power loss due to the fiber jumpers used to connect to the network.
- The second step is the insertion of the fiber under test and the power measurement of the connected elements (jumpers + fiber under test).

The difference between the two power readings gives the insertion loss of the fiber, provided in decibels (dB).

$$Loss\ (dB) = Power\ In - Power\ Out$$

This is a unidirectional measurement; however, it can be performed bidirectionally for operational purposes.

Note: The total loss provided by the OTDR can also be used at the same time as the splice/connector and distance measurements. The ITU-T G.650.1 defines backscatter measurement as the second alternative method for the measurement of attenuation.

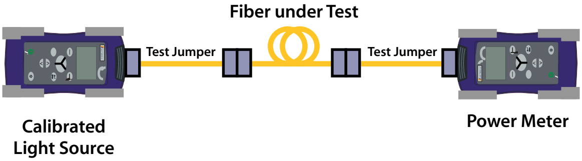


Figure 74: Insertion loss method (2 steps) to measure the attenuation along a fiber link

Loss test sets will provide wavelengths which will be representative of the transmission signal; however, using multiple wavelengths enables easy detection of possible fiber installation default, such as bends. For single-mode applications, the recommendation is to use a 1310/1550/1625 nm loss test set.

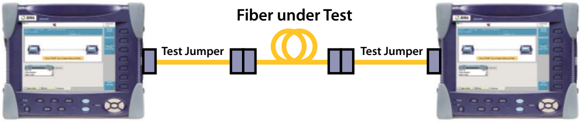
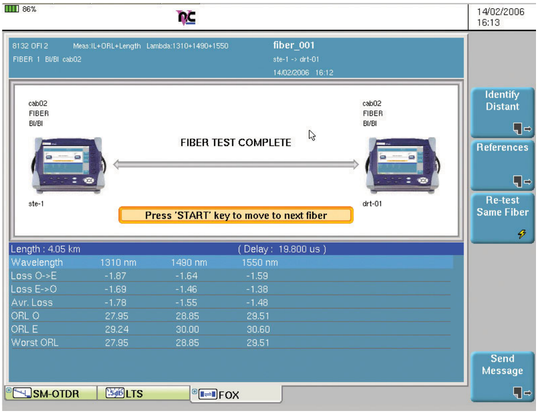


Figure 75: JDSU bidirectional IL measurement solution integrated into the T-BERD/MTS-8000 platform (also includes ORL and length measurement)



14/02/2006
16:13

8132 OFI 2 Meas:IL+ORL+Length Lambda:1310+1490+1550
FIBER 1 BI/BI cab02

fiber_001
ste-1 -> drt-01
14/02/2006 16:12

cab02
FIBER
BI/BI
ste-1

FIBER TEST COMPLETE

cab02
FIBER
BI/BI
drt-01

Press 'START' key to move to next fiber

Length : 4.05 km (Delay : 19.800 us)

Wavelength	1310 nm	1490 nm	1550 nm
Loss O->E	-1.87	-1.64	-1.59
Loss E->O	-1.69	-1.46	-1.38
Avr. Loss	-1.78	-1.55	-1.48
ORL O	27.95	28.85	29.51
ORL E	29.24	30.00	30.60
Worst ORL	27.95	28.85	29.51

Figure 76: Bidirectional IL measurement results in display of the JDSU T-BERD/MTS-8000 (also includes ORL and length measurement)

4.4.3 Optical Return Loss Measurements

The optical return loss (ORL) of a link represents the portion of the light reflected back to the laser source by the link.

The ORL is therefore the ratio between the transmitted power and the received power at the fiber origin. This return of the light is due to different physical phenomena such as reflections on connectors, Rayleigh back-scattering, and diffusion.

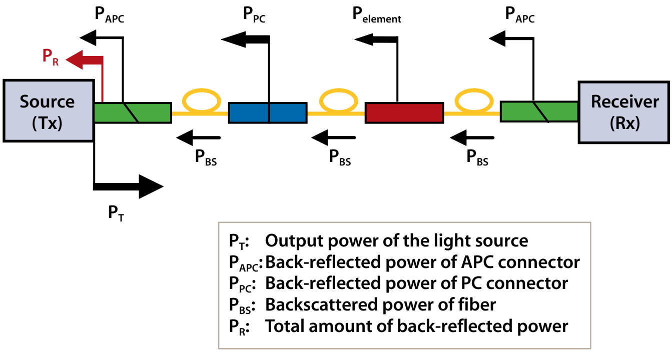


Figure 77: Element of ORL

To measure the ORL of a fiber link, a laser source and a power meter using the same test port are connected to the fiber under test. This method is called an optical continuous wave reflectometry (OCWR). The laser source sends a signal at a known power level into the fiber, and the power meter measures the reflected power level at the same location.

Prior to performing an ORL measurement, it is necessary to take an ORL reference measurement. As the test set will be connected with a jumper, it is necessary to subtract the jumper ORL value from the total ORL reading in order to display only the ORL of the link, and not the ORL of the link plus the jumper.

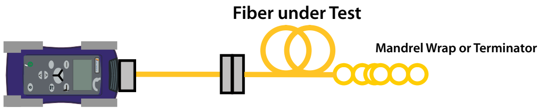


Figure 78: Stand-alone ORL meter ORL-55

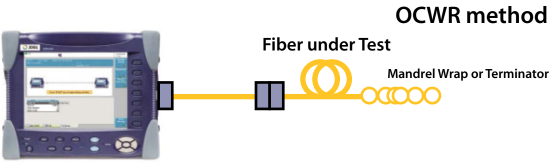


Figure 79:T-BERD/MTS-8000 with OFI module

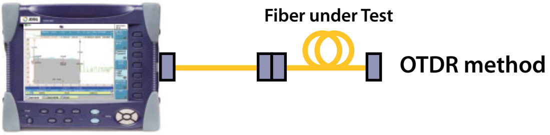


Figure 80:T-BERD/MTS-8000 with OTDR module

An alternative solution is to measure the ORL with an OTDR.

The ORL meter provides wavelengths that are representative of the transmission signal. The recommendation is to use a 1310/1550 nm ORL meter or OTDR, with 1625 nm optionally.

This measurement is usually performed at the end of the installation, for commissioning purposes and is unidirectional, except if the transmission is intended to be bidirectional.

Note: If the fiber is open at the far end of the test, it is recommended to use a terminator or to wrap the fiber around a mandrel to reduce the effect of glass-to-air reflection, which will induce error in the ORL measurement.

4.4.4 Distance and Event Characterization Using an OTDR

Fiber links are made of sections of fiber cables that are connected using splices (fusion or mechanical) and connectors. Each section and event has to be characterized. This could be called “event characterization.” It consists of measuring attenuation of the fiber section, loss of each event, the associated reflectance, and related distances.

The OTDR is the only instrument that can measure splice loss, connector loss, and reflectance. It can obtain the “signature” of the fiber with distance and loss/reflectance information for each event present along the link. A laser source sends a series of pulses into the fiber and a photodiode receiver analyzes the backscattered and reflected light coming back.

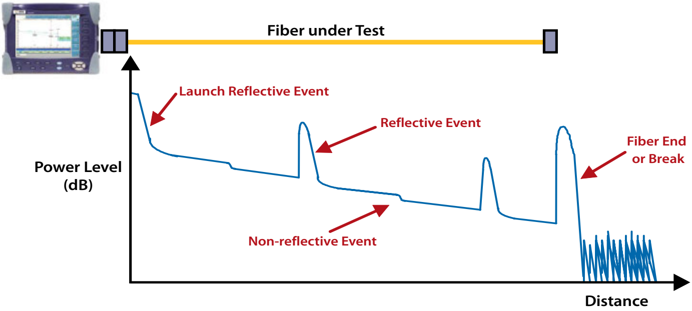
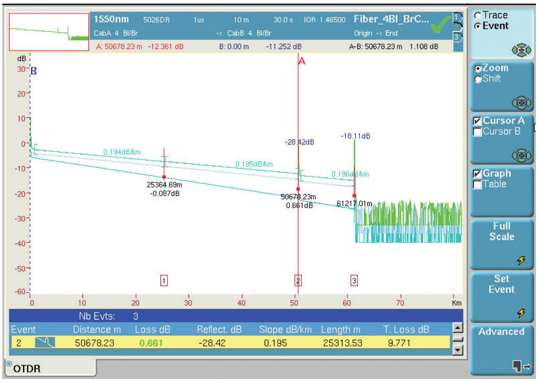


Figure 81: T-BERD/MTS-8000 with OTDR module and resulting trace

The OTDR test is performed using wavelengths which characterize the fiber around the transmission system, for example, 1550 nm for DWDM C-band transmission; however, using multiple wavelengths enables easy detection of a possible fiber installation default, such as bends. It is usually recommended to use a 1310/1550/1625 nm OTDR.



1550nm 5026DR 1us 10 m 30.0 s IOR: 1.46500 Fiber_4BI_BrC...
CabA 4 Bl/Br -> CabB 4 Bl/Br Origin -> End
A: 50678.23 m -12.361 dB B: 0.00 m -11.252 dB A-B: 50678.23 m 1.108 dB

Nb Evts: 3

Event	Distance m	Loss dB	Reflect. dB	Slope dB/km	Length m	T. Loss dB
2	50678.23	0.661	-28.42	0.195	25313.53	9.771

Figure 82: Multi-wavelength OTDR measurement with the JDSU OTDR module range

Note: If connectors at the extremities of the link have to be qualified, then use launch cables at each end. Fiber length for launch cables is usually 1 km.

Perform OTDR measurements in both directions of the fiber link. For each splice/connector, calculate the average loss to measure the "true" value by eliminating possible differences in backscattering coefficients between fiber sections, which avoids inaccurate loss readings such as "gainers." This measurement is even more important if the link contains different fiber types or different manufactured fibers. This process is known as "bidirectional OTDR testing."

1550 nm 5026DR 300ns 10 m 90 s IOR: 1.47600

--- N30 STE <-> GNT

A: 14637.76 m B: 0.00 m -8.130 dB A-B: 14637.76 m

Nb Evts: 7

Event	Distance OE m	Distance EO m	Loss OE dB	Loss EO dB	Loss OEO dB	Length m	T. Loss dB
1	0.00	10114.95	0.194	0.251	0.222	2031.11	-0.000
2	914.00	9180.64	-0.018	0.068	0.025	903.85	0.375
3	2599.83	7494.81	0.123	-0.076	0.024	1685.82	0.688
4	3554.45	6550.34	-0.028	0.103	0.038	944.47	1.000
5	7941.66	2183.45	0.057	0.062	0.060	4387.21	1.836
6	10114.95	0.00	0.463	0.226	0.345	2163.14	2.312
7	12125.75					2010.80	3.176

Figure 83: Bidirectional OTDR analysis with the JDSU T-BERD/MTS platforms

4.4.5 Chromatic Dispersion Measurements

Measure CD over a given wavelength range and correlate the results to the transmission system limits according to the bit rate being implemented.

Several methods can be used to measure CD. The Phase Shift method is the most versatile and requires connecting a source (broadband or narrowband) and a receiver (phase meter) to each end of the link.

Note: If using the pulse delay method, access to only one end is possible but depends on the distance to be measured.

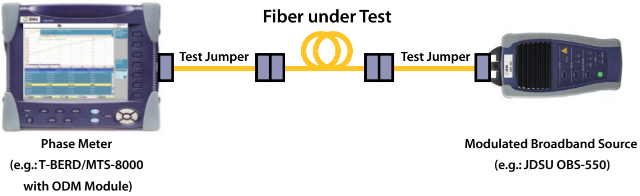
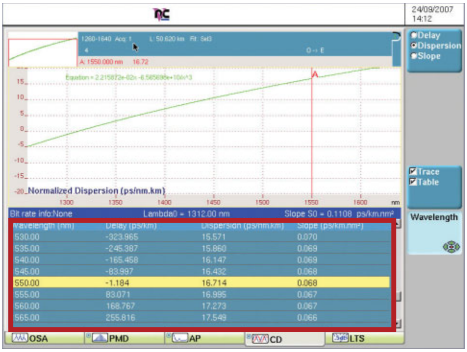


Figure 84: CD test setup with the JDSU solution

CD measurement is typically performed unidirectionally with the wavelength measurement range at least equivalent to transmission system: C band or C+L band. However, the full band (1260 to 1640 nm) solution allows for accurate measurement of the zero dispersion wavelength of G.652 fiber and is compatible with any transmission scenario (including full band CWDM).



Bit rate info:None Lambda0 = 1312.00 nm Slope S0 = 0.1108 ps/km.nm²

Wavelength (nm)	Delay (ps/km)	Dispersion (ps/nm.km)	Slope (ps/km.nm²)
530.00	-323.965	15.571	0.070
535.00	-245.387	15.860	0.069
540.00	-165.458	16.147	0.069
545.00	-83.997	16.432	0.068
550.00	-1.184	16.714	0.068
555.00	83.071	16.995	0.067
560.00	168.767	17.273	0.067
565.00	255.816	17.549	0.066

Parameters to correlate to the equipment specifications:
- Total link dispersion
- Dispersion slope
- Zero dispersion wavelength and associated slope

Figure 85: CD results with the JDSU Phase Shift method (ODM module)

4.4.6 Polarization Mode Dispersion Measurements

PMD is the most complex phenomenon to deal with as it varies randomly with time. It is important to determine the PMD delay of a fiber link so that it can be correlated to the transmission system limit, providing an understanding of the margin between the measured and the defined limits.

The PMD measurement range should be compatible with the transmission bit rate. In order to cover a broad range of field applications, it must measure between 0.1 and 60 ps for accurate characterizations of fiber links for transmission rates such as 10 and 40 Gbps.

Several test methods are used to measure PMD in the field. The most relevant and versatile is the Fixed Analyzer method as it can be built without any moving parts for better field robustness and durability.

The broadband source sends a polarized light that is analyzed by a spectrum analyzer after passing through a polarizer.

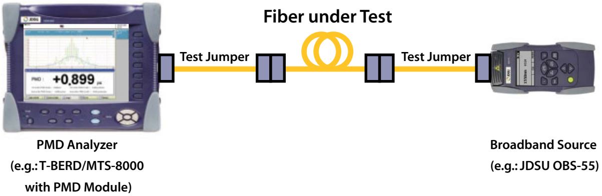


Figure 86: PMD test setup with the JDSU solution

Figure 87 shows an FFT graph displayed together with the Gaussian curve. The PMD delay and calculated second-order delay are provided together with the coefficients after setting up the distance.

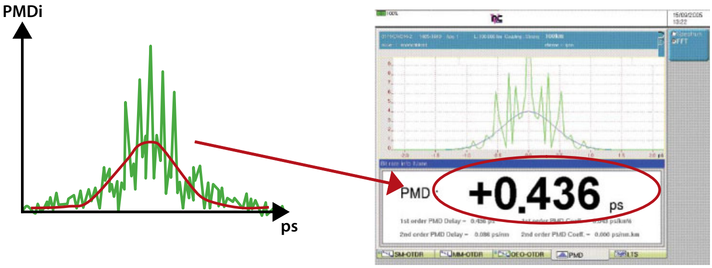


Figure 87: PMD measurement display with the JDSU Fixed Analyzer method in the T-BERD/MTS platform

PMD measurements are typically performed unidirectionally. When PMD results are too close to the system limits, a long-term measurement analysis may be required to get a better picture of the variation over the time.

4.4.7 Attenuation Profile Measurements

Every fiber presents varying levels of attenuation across the transmission spectrum. The purpose of the AP measurement is to represent the attenuation as a function of the wavelength.

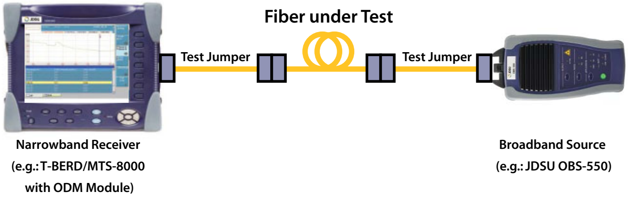


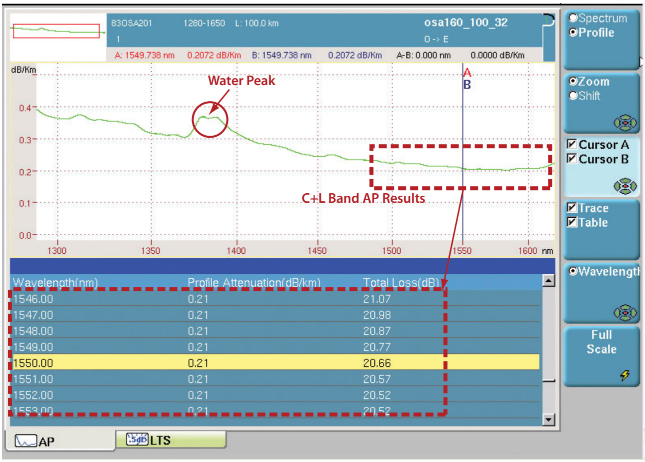
Figure 88: PMD test setup with the JDSU solution

A reference measurement of the source and fiber jumpers is required prior to performing the measurements.

The receiver records the attenuation per wavelength of the source used for transmission that can then be used to determine amplifier locations and specifications and could have an impact on channel equalization (macro or micro-bends).

Obtaining the normalized attenuation profile (attenuation given in dB/km) requires dividing the loss of a given wavelength by the link distance itself in kilometers.

Spectral attenuation measurements are typically performed unidirectionally with the wavelength measurement range at least equivalent to transmission system: C band or C+L band.



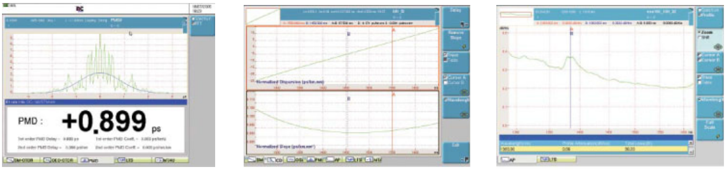
Wavelength(nm)	Profile Attenuation(dB/km)	Total Loss(dB)
1546.00	0.21	21.07
1547.00	0.21	20.98
1548.00	0.21	20.87
1549.00	0.21	20.77
1550.00	0.21	20.66
1551.00	0.21	20.57
1552.00	0.21	20.52
1553.00	0.21	20.52

Figure 89: Full band attenuation profile results with JDSU ODM module in the T-BERD/MTS platform

4.4.8 Test Results Overview

After performing each test, the fiber link is considered characterized. System engineers can then analyze the resulting data and generate a measurement report to be archived in the database.

Connector Quality Insertion Loss OTDR



Polarization Mode Dispersion Chromatic Dispersion Attenuation Profile

Figure 90: Summary of link characterization tests

4.5 The Work of Many Performed by One

4.5.1 Handling and Time-Saving Functions

The major constraint in fiber characterization testing is the number of connections and disconnections made. Most current fiber characterization tools (modular test platforms with multiple modules) require several jumper/fiber connections and disconnections in order to complete the suite of tests—therefore technicians must move the fiber under test or the lead-in jumper from one module to another, with up to five connections and disconnections (depending on the number of tests performed).

A typical testing scenario involves four fiber characterization tests (for example, OTDR, CD, PMD, and AP) on a 144-fiber cable, thus 576 connections (144 fibers four times) and 576 disconnections. These repetitive operations increase the possibility of errors and represent the most time-consuming part of the process in characterizing fiber cable.

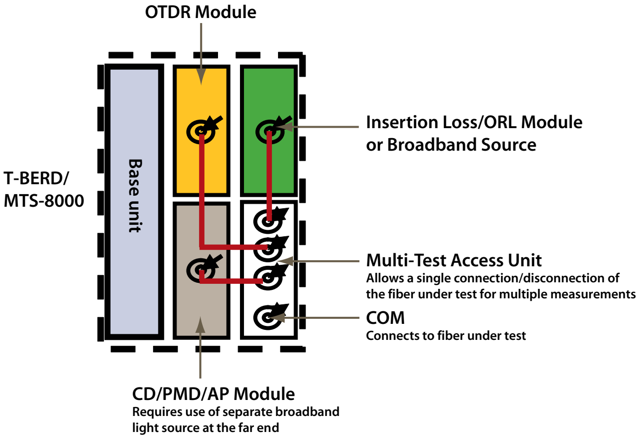


Figure 91: Schematic of the T-BERD/MTS-8000 MTAU and the associated plug-in module connections

To reduce the time performing these tedious multi-step tests and the possibility for error, JDSU has developed an integrated and portable solution for the T-BERD/MTS-8000, called the Multi-Test Access Unit (MTAU). With the MTAU, technicians simply connect all test functions to one module and make only one connection and disconnection per fiber under test.

Figure 92: T-BERD/MTS-8000 configured with the MTAU module connected to the fiber characterization test modules

4.5.2 On-Line Report Generation

Using the traditional techniques for completion of the test, technicians must manually compile all results into a single report that typically involves downloading, sorting, and integrating thousands of values into a single, professional-looking file. Even if the tests are performed without error, the process of generating the report introduces the potential for documentation errors and is very time consuming.

PC software, such as JDSU FiberCable can compile all the test results and produces a fiber characterization test report. The innovative JDSU solution not only generates the needed report, but also integrates the sequence into the fiber characterization test process to free technicians from performing further post-processing at the end of the job.

4.6 Fiber Characterization Post-Processing Report Generation

If the automated fiber characterization test solution is not used, then one must consider the traditional report generation method.

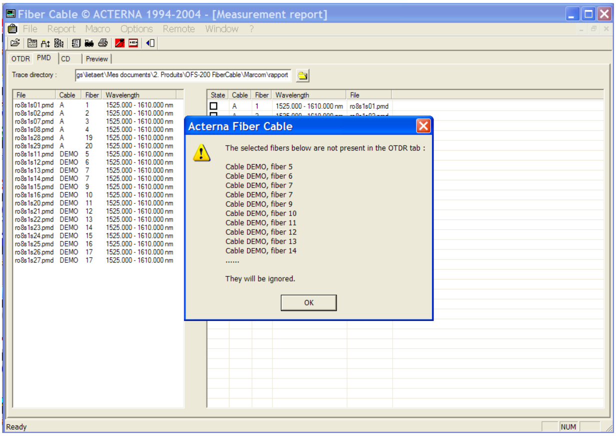
The use of such a fiber characterization report is critical during all steps of the network life cycle, which pushes the report quality further ahead. It will be generated in a professional format and include all relevant information related to the link as well as detailed measurement results. Furthermore, it will fulfill the customer's requirements in terms of information content and document format.

4.6.1 Measurement Result Consistency

As each value defines the network's ability to transmit at a given bit rate, it is mandatory to ensure the consistency of the report and to reduce the risk of manipulation errors. Dealing with this huge amount of data can result in mixing OTDR traces from cable A with PMD values from cable B and so on. This reporting software allows reliable compilation of all data into a single staged process, with step-by-step check points for permanent result consistency. The JDSU FiberCable software not only compiles all the data together, but it also screens the results to verify compatibility within the same fiber cable, providing an error-free report!

4.6.2 Report Generation

Fiber installers or test contractors characterizing fiber cannot afford to spend excessive time generating reports. It is also unacceptable to postpone job completion due to a delay in the acceptance report document. Therefore,“time to prepare the report” is a critical but often overlooked part of the fiber characterization workload process: a fiber characterization contract is fulfilled only when the final report is provided to the end user. JDSU FiberCable software eliminates the need to bridge all of the independent reports and



Trace directory : gs\lietaert\Mes documents\2. Produits\OFS-200 FiberCable\Marcom\rapport

File	Cable	Fiber	Wavelength
ro8s1s01.pmd	A	1	1525.000 - 1610.000 nm
ro8s1s02.pmd	A	2	1525.000 - 1610.000 nm
ro8s1s07.pmd	A	3	1525.000 - 1610.000 nm
ro8s1s08.pmd	A	4	1525.000 - 1610.000 nm
ro8s1s28.pmd	A	19	1525.000 - 1610.000 nm
ro8s1s29.pmd	A	20	1525.000 - 1610.000 nm
ro8s1s11.pmd	DEMO	5	1525.000 - 1610.000 nm
ro8s1s12.pmd	DEMO	6	1525.000 - 1610.000 nm
ro8s1s13.pmd	DEMO	7	1525.000 - 1610.000 nm
ro8s1s14.pmd	DEMO	7	1525.000 - 1610.000 nm
ro8s1s15.pmd	DEMO	9	1525.000 - 1610.000 nm
ro8s1s16.pmd	DEMO	10	1525.000 - 1610.000 nm
ro8s1s20.pmd	DEMO	11	1525.000 - 1610.000 nm
ro8s1s21.pmd	DEMO	12	1525.000 - 1610.000 nm
ro8s1s22.pmd	DEMO	13	1525.000 - 1610.000 nm
ro8s1s23.pmd	DEMO	14	1525.000 - 1610.000 nm
ro8s1s24.pmd	DEMO	15	1525.000 - 1610.000 nm
ro8s1s25.pmd	DEMO	16	1525.000 - 1610.000 nm
ro8s1s26.pmd	DEMO	17	1525.000 - 1610.000 nm
ro8s1s27.pmd	DEMO	17	1525.000 - 1610.000 nm

State	Cable	Fiber	Wavelength	File
☐	A	1	1525.000 - 1610.000 nm	ro8s1s01.pmd

Acterna Fiber Cable

The selected fibers below are not present in the OTDR tab :

Cable DEMO, fiber 5
Cable DEMO, fiber 6
Cable DEMO, fiber 7
Cable DEMO, fiber 7
Cable DEMO, fiber 9
Cable DEMO, fiber 10
Cable DEMO, fiber 11
Cable DEMO, fiber 12
Cable DEMO, fiber 13
Cable DEMO, fiber 14
……

They will be ignored.

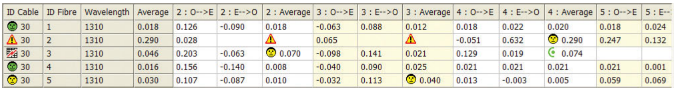
OK

Figure 93: Consistency tests are performed by the JDSU FiberCable software during the report generation process

information into one single document. The software considerably cuts down the reporting procedure compared to any standard solutions with independent results management.

4.6.3 Error-Free Fiber Characterization Report

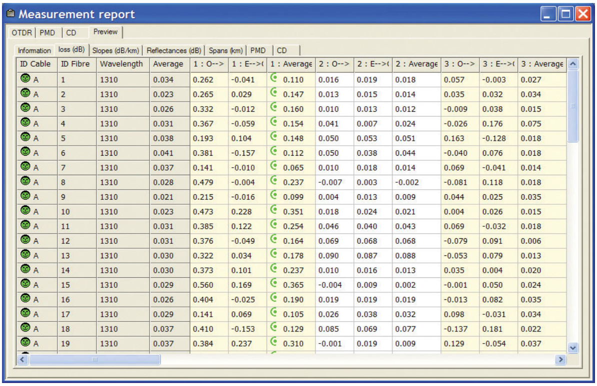
In addition to reducing report generation time it is also imperative to generate an accurate report. Therefore, the automation process of the software must be monitored step by step. Dialog boxes and pop-up windows warn technicians of potential problems during the report generation process. In addition to the different check points, a set of thresholds and other criteria can be defined, offering additional information about the report quality. It provides corresponding pass/fail information throughout the result tables, displaying different types of warnings when applicable.



ID Cable	ID Fibre	Wavelength	Average	2 : O-->E	2 : E-->O	2 : Average	3 : O-->E	3 : E-->O	3 : Average	4 : O-->E	4 : E-->O	4 : Average	5 : O-->E	5 : E--
☺ 30	1	1310	0.018	0.126	-0.090	0.018	-0.063	0.088	0.012	0.018	0.022	0.020	0.018	0.024
⚠ 30	2	1310	0.290	0.028		⚠	0.065		⚠	-0.051	0.632	☹ 0.290	0.247	0.132
▨ 30	3	1310	0.046	0.203	-0.063	☹ 0.070	-0.098	0.141	0.021	0.129	0.019	◔ 0.074		
☺ 30	4	1310	0.016	0.156	-0.140	0.008	-0.040	0.090	0.025	0.021	0.021	0.021	0.021	0.001
☹ 30	5	1310	0.030	0.107	-0.087	0.010	-0.032	0.113	☹ 0.040	0.013	-0.003	0.005	0.059	0.069

Figure 94: Different alarms enable technicians to locate errors in the report

Because compiling the data into a spreadsheet proves tedious, technicians prefer reviewing all the results before starting the final stage. To address this issue, FiberCable offers a complete preview of the report, identifying missing information and inconsistencies. This step in the report generation process avoids multiple result compilations that could significantly increase the time required to generate the final report.



ID Cable	ID Fibre	Wavelength	Average	1 : O-->	1 : E-->(	1 : Average	2 : O-->	2 : E-->(	2 : Average	3 : O-->	3 : E-->(	3 : Average
☺ A	1	1310	0.034	0.262	-0.041	0.110	0.016	0.019	0.018	0.057	-0.003	0.027
☺ A	2	1310	0.023	0.265	0.029	0.147	0.013	0.015	0.014	0.035	0.032	0.034
☺ A	3	1310	0.026	0.332	-0.012	0.160	0.010	0.013	0.012	-0.009	0.038	0.015
☺ A	4	1310	0.031	0.367	-0.059	0.154	0.041	0.007	0.024	-0.026	0.176	0.075
☺ A	5	1310	0.038	0.193	0.104	0.148	0.050	0.053	0.051	0.163	-0.128	0.018
☺ A	6	1310	0.041	0.381	-0.157	0.112	0.050	0.038	0.044	-0.040	0.076	0.018
☺ A	7	1310	0.037	0.141	-0.010	0.065	0.010	0.018	0.014	0.069	-0.041	0.014
☺ A	8	1310	0.028	0.479	-0.004	0.237	-0.007	0.003	-0.002	-0.081	0.118	0.018
☺ A	9	1310	0.021	0.215	-0.016	0.099	0.004	0.013	0.009	0.044	0.025	0.035
☺ A	10	1310	0.023	0.473	0.228	0.351	0.018	0.024	0.021	0.004	0.026	0.015
☺ A	11	1310	0.031	0.385	0.122	0.254	0.046	0.040	0.043	0.069	-0.032	0.018
☺ A	12	1310	0.031	0.376	-0.049	0.164	0.069	0.068	0.068	-0.079	0.091	0.006
☺ A	13	1310	0.030	0.322	0.034	0.178	0.090	0.087	0.088	-0.053	0.079	0.013
☺ A	14	1310	0.030	0.373	0.101	0.237	0.010	0.016	0.013	0.035	0.004	0.020
☺ A	15	1310	0.029	0.560	0.169	0.365	-0.004	0.009	0.002	-0.001	0.050	0.024
☺ A	16	1310	0.026	0.404	-0.025	0.190	0.019	0.019	0.019	-0.013	0.082	0.035
☺ A	17	1310	0.029	0.141	0.069	0.105	0.026	0.038	0.032	0.098	-0.031	0.034
☺ A	18	1310	0.037	0.410	-0.153	0.129	0.085	0.069	0.077	-0.137	0.181	0.022
☺ A	19	1310	0.037	0.384	0.237	0.310	-0.001	0.019	0.009	0.129	-0.054	0.037

Figure 95: Complete fiber characterization report preview

A professional, easy-to-read fiber characterization report format combines all the tests' results, alarms, and related information, providing the end user with comprehensive information about the installed fibers and serving as the final sign-off for the installation. In addition, managers or technicians can regularly and easily consult this report when fiber maintenance, repair, or system upgrades are implemented.

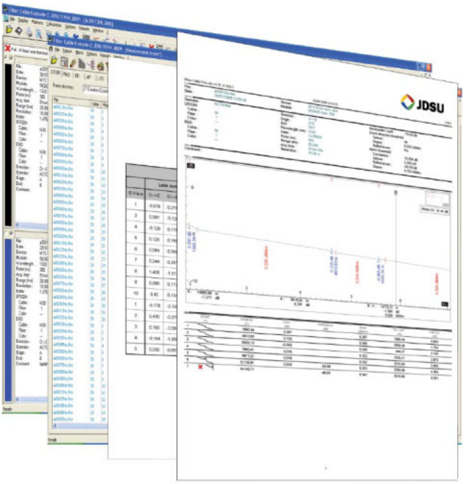
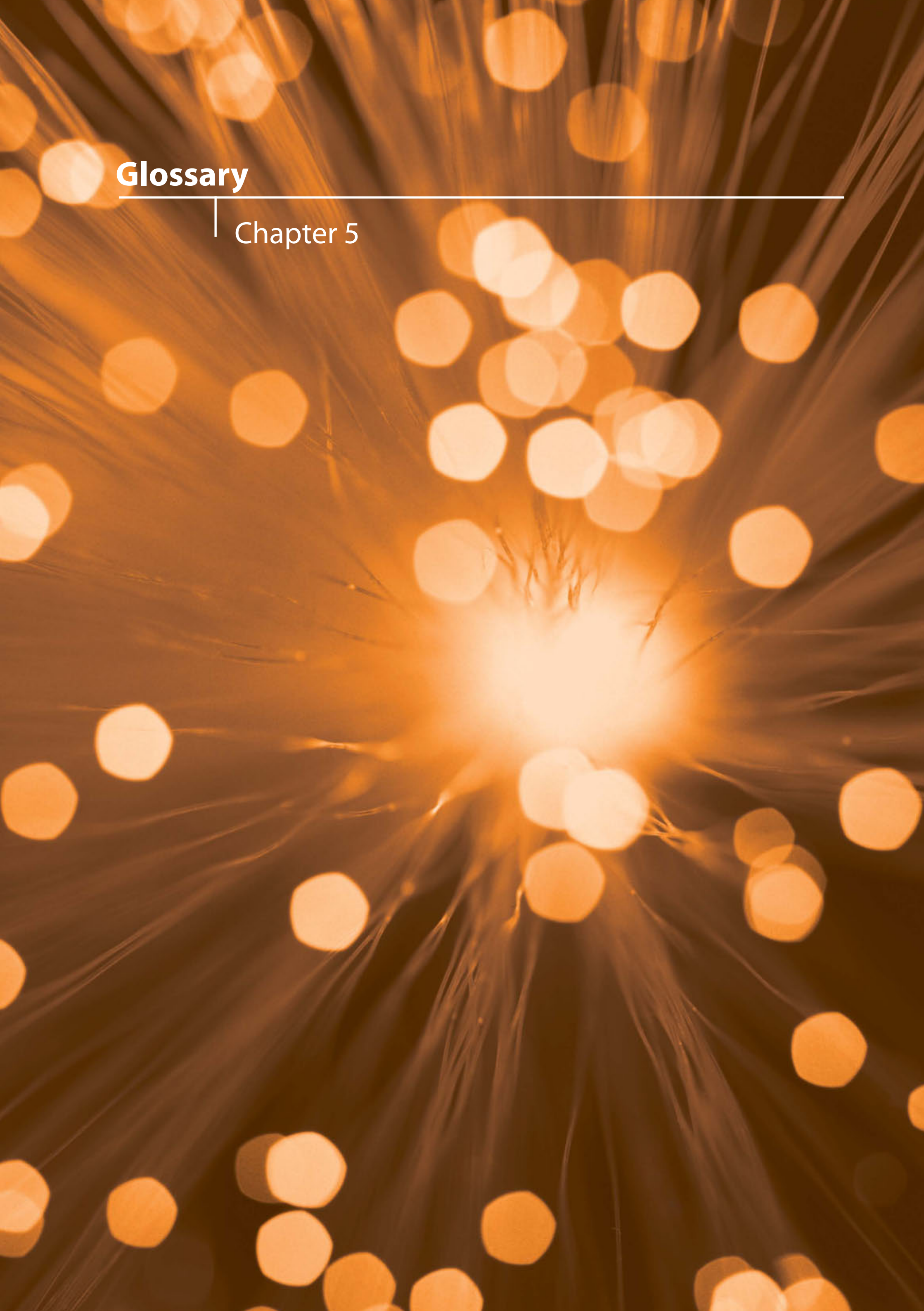


Figure 96: JDSU fiber characterization measurement report

4.7 Conclusion

Failure to characterize the fiber prior to installation of system components can result in substantial delays in service provisioning or an increase in the time to repair, leading to project postponements and/or missed turn-up commitments. Detailed records must be generated for test parameters that can affect the transmission quality, and system limits must be considered for future provisioning.



Glossary

Chapter 5

$<\Delta\tau>$	mean DGD (expressed in ps)
AP	attenuation profile (measured in dB or dB/km)
APC	angled polished connector
C-Band	DWDM wavelength range from 1530 to 1565 nm
CD	chromatic dispersion (expressed in ps/nm)
CS-RZ	carrier-suppressed return to zero
CWDM	coarse wavelength division multiplexing
D	chromatic dispersion coefficient (expressed in ps/nm x km)
D_{1550}	chromatic dispersion coefficient at the wavelength of 1550 nm (expressed in ps/nm x km)
DA	dispersion accommodation
dB	decibel
DCF	dispersion-compensation fiber
DCM	dispersion-compensation module
DFE	decision feedback equalizer
DGD	Differential Group Delay (expressed in ps)
D_{max}	maximum chromatic dispersion coefficient (expressed in ps/nm x km)
D_{min}	minimum chromatic dispersion coefficient (expressed in ps/nm x km)
DQPSK	differential quadrature phase shift keying
DSF	dispersion-shifted fiber
$\Delta\tau$	expression of the Differential Group Delay (in ps)
DWDM	dense wavelength division multiplexing
EC	extrema counting
EDFA	erbium doped fiber amplifier

FA	Fixed Analyzer
FBG	fiber Bragg grating
FEC	forward error correction
FFE	feed-forward equalizer
FOTP	Fiber Optic Test Procedure
FT	Fourier transform
FUT	fiber under test
G.652	Characteristics of a single-mode optical fiber and cable.
G.652.A	Contains the recommended attributes and values needed to support applications such as those recommended in ITU-T Recs G.957 and G.691 up to STM-16, as well as 10 Gbps up to 40 km (Ethernet) and STM-256 for ITU-T Rec. G.693.
G.652.B	Contains recommended attributes and values needed to support higher bit rate applications, up to STM-64, such as some in ITU-T Recs G.691 and G.692, STM-256 for some applications in ITU-T Recs G.693 and G.959.1.
G.652.C	Similar to G.652.A, but allows transmissions in portions of an extended wavelength range from 1360 to 1530 nm.
G.652.D	Similar to G.652.B, but allows transmissions in portions of an extended wavelength range from 1360 to 1530 nm.
G.653	ITU-T Recommendation for characteristics of a dispersion-shifted singlemode optical fibre and cable.
G.655	ITU-T Recommendation for characteristics of a non-zero dispersion-shifted single-mode optical fiber and cable.

G.656	ITU-T Recommendation for characteristics of a fiber and cable with non-zero dispersion for wideband optical transport.
G.671	ITU-T Recommendation for transmission characteristics of optical components and subsystems.
G.691	ITU-T Recommendation for optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers.
G.693	ITU-T Recommendation for optical interfaces for intra-office systems.
G.798	ITU-T Recommendation that covers the functional requirements of optical transport network functionality within equipment.
G.957	ITU-T Recommendation for optical interfaces for equipments and systems relating to the synchronous digital hierarchy.
Gbps	Gigabit per second or 1 billion bit per second (describes the data rate of a transmission signal)
GINTY	Generalized Interferometric method
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IL	insertion loss (measured in dB)
IOR	index of refraction
ISI	inter-symbol interference
ITU	International Telecommunication Union
ITU-T	ITU standardization sector
JME	Jones-Matrix-Eigen analysis

Λ	period
L	length of fiber
λ_0	zero chromatic dispersion wavelength (expressed in nm)
λ_{max0}	maximum zero dispersion wavelength (expressed in nm)
λ_{min0}	minimum zero dispersion wavelength (expressed in nm)
L-Band	DWDM wavelength range from 1565 to 1610 nm
MAN	metropolitan access network
MFD	mode field diameter
MLSE	maximum-likelihood sequence estimators
MTAU	Multi-Test Access Unit
NDSF	non-dispersion-shifted fiber
N_e	number of extrema
n_{eff}	effective index of refraction
nm	nanometer
NRZ	non-return to zero
NZ-DSF	non-zero dispersion-shifted fiber
OC-192	optical carrier level describing a digital signal carried on SONET fiber optic network at a data rate of approx. 10 Gbps
OC-48	optical carrier level describing a digital signal carried on SONET fiber optic network at a data rate of approx. 2.5 Gbps
OC-768	optical carrier level describing a digital signal carried on SONET fiber optic network at a data rate of approx. 40 Gbps

OCWR	optical continuous wave reflectometry
OH-	hydroxyl anion called hydroxide is a molecule consisting of one oxygen and one hydrogen atom
OOK	on-off keyed
ORL	optical return loss (measured in dB)
OSA	optical spectrum analyzer
OSNR	optical signal-to-noise ratio (measured in dB)
OTDR	optical time domain reflectometer
PDC	passive dispersion compensator
PMD	polarization mode dispersion (expressed in ps)
PMF	polarization maintaining fiber
ps	picosecond
PSA	Poincare Sphere analysis
PSP	principle state of polarization
ROADM	reconfigurable optical add/drop multiplexer
RZ	return to zero
S	chromatic dispersion slope (expressed in ps/nm^2)
S_0	chromatic dispersion slope at the zero dispersion wavelength, also called zero dispersion slope (expressed in ps/nm^2)
S_{0max}	maximum dispersion slope at the zero dispersion wavelength
S_{1550}	chromatic dispersion slope at the wavelength of 1550 nm
SDH	synchronous digital hierarchy
SLED	super luminescent emitting diode
SONET	synchronous optical network

SOP	state of polarization
SSMF	standard single-mode fiber
STM-16	Synchronous Transport Module describing a digital signal carried on SDH fiber optic network at a data rate of approx. 2.5 Gbps
STM-256	Synchronous Transport Module describing a digital signal carried on SDH fiber optic network at a data rate of approx. 40 Gbps
STM-64	Synchronous Transport Module describing a digital signal carried on SDH fiber optic network at a data rate of approx. 10 Gbps
TEF	transversal electrical filter
TIA	Telecommunications Industry Association
TINTY	Traditional Interferometric method
WAN	wide area network
Δn	index profile or difference between the core IOR and the cladding IOR

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