



Reference Guide to Fiber Optic Testing

SECOND EDITION

Volume 1



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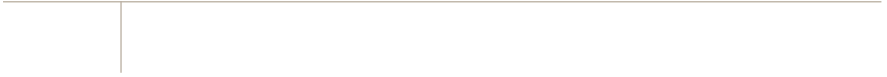
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Principles of Light Transmission on a Fiber

Chapter 1



1.1 Optical Communications

The principle of an optical communications system is to transmit a signal through an optical fiber to a distant receiver. The electrical signal is converted into the optical domain at the transmitter and is converted back into the original electrical signal at the receiver. Fiber optic communication has several advantages over other transmission methods, such as copper and radio communication systems.

- A signal can be sent over long distances (200 km) without the need for regeneration.
 - The transmission is not sensitive to electromagnetic perturbations. In addition, the fiber does not conduct electricity and is practically insensitive to RF interferences.
 - Fiber optic systems provide greater capacity than copper or coaxial cable systems.
 - The fiber optic cable is much lighter and smaller than copper cable. Therefore, fiber optic cables can contain a large number of fibers in a much smaller area. For example, a single fiber cable can consist of 144 fibers.
 - Optical fiber is reliable and very flexible.
 - Optical fiber has a lifetime greater than 25 years (compared with 10 years for satellite communications systems).
 - Operating temperatures for optical fiber vary, but they typically range from -40° to $+80^{\circ}\text{C}$.
-

Three main factors can affect light transmission in an optical communication system:

1. **Attenuation:** As the light signal travels through the fiber, it loses optical power due to absorption, scattering, and other radiation losses. At some point, the power level may become too weak for the receiver to distinguish between the optical signal and the background noise.
2. **Bandwidth:** Since the light signal is composed of different frequencies, the fiber limits the highest and lowest frequencies and reduces the information carrying capacity.
3. **Dispersion:** As the light signal travels through the fiber, the light pulses spread or broaden and limit the information carrying capacity at very high bit rates or for transmission over very long distances.

1.2 Fiber Design

An optical fiber is composed of a very thin glass rod, which is surrounded by a plastic protective coating. The glass rod contains two parts: the inner portion of the rod (or core) and the surrounding layer (or cladding). Light injected into the core of the glass fiber follows the physical path of the fiber due to the total internal reflection of the light between the core and the cladding.



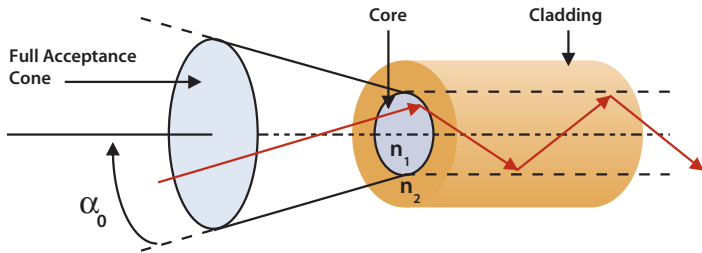
The composition of optical fiber

1.3 Transmission Principles

A ray of light enters a fiber at a small angle α . The capability (maximum acceptable value) of the fiber cable to receive light through its core is determined by its numerical aperture (NA).

$$NA = \sin \alpha_0 = \sqrt{n_1^2 - n_2^2}$$

Where α_0 is the maximum angle of acceptance (that is, the limit between reflection and refraction), n_1 is the core refractive index, and n_2 is the cladding refractive index.



The injection of light into a fiber

The full acceptance cone is defined as $2\alpha_0$.

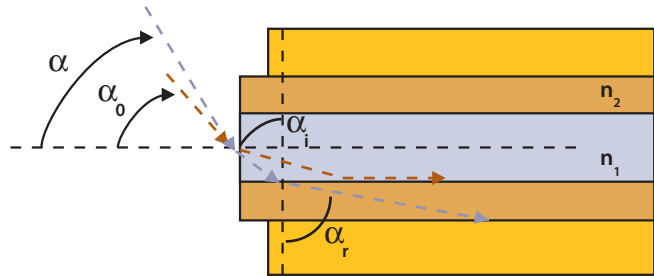
1.3.1 Light Propagation

The propagation of a ray of light in optical fiber follows Snell-Descartes' law. A portion of the light is guided through the optical fiber when injected into the fiber's full acceptance cone.

1.3.1.1 Refraction

Refraction is the bending of a ray of light at an interface between two dissimilar transmission media. If $\alpha > \alpha_0$, then the ray is fully refracted and is not captured by the core.

$$n_1 \sin \alpha_i = n_2 \sin \alpha_r$$



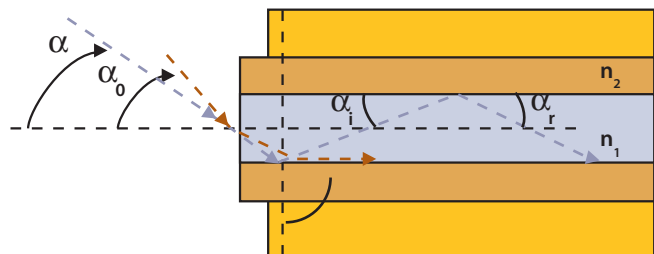
Refraction of light

1.3.1.2 Reflection

Reflection is the abrupt change in direction of a light ray at an interface between two dissimilar transmission media. In this case, the light ray returns to the media from which it originated.

If $\alpha < \alpha_0$, then the ray is reflected and remains in the core.

$$\alpha_i = \alpha_r$$



Reflection of light

1.3.1.3 Propagation Principle

Light rays enter the fiber at different angles and do not follow the same paths. Light rays entering the center of the fiber core at a very low angle will take a relatively direct path through the center of the fiber. Light rays entering the fiber core at a high angle of incidence or near the outer edge of the fiber core will take a less direct, longer path through the fiber and will traverse the fiber more slowly. Each path, resulting from a given angle of incidence and a given entry point, will give rise to a mode. As the modes travel along the fiber, each of them is attenuated to some degree.

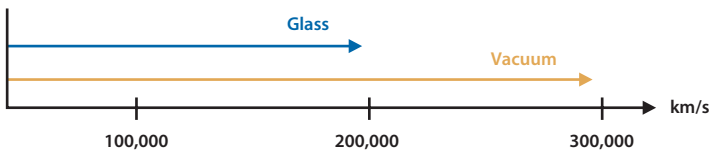
1.3.2 Velocity

The speed at which light travels through a transmission medium is determined by the refractive index of the transmission medium. The refractive index (n) is a unitless number, which represents the ratio of the velocity of light in a vacuum to the velocity of light in the transmission medium.

$$n = c/v$$

Where n is the refractive index of the transmission medium, c is the speed of light in a vacuum (2.99792458×10^8 m/s), and v is the speed of light in the transmission medium.

Typical values of n for glass, such as optical fiber, are between 1.45 and 1.55. As a rule, the higher the refractive index, the slower the speed in the transmission medium.



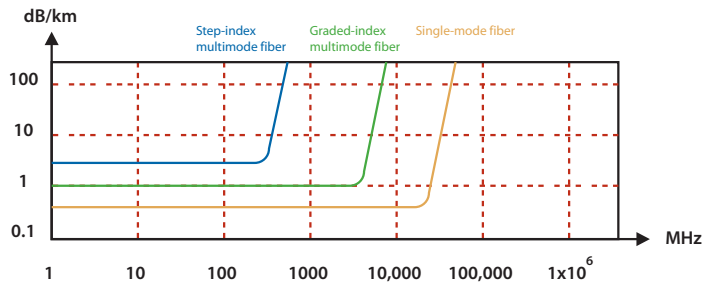
Comparing the speed of light through different transmission mediums

Typical manufacturer's values for Index of Refraction are:

- Corning® LEAF®
 - n = 1.468 at 1550 nm
 - n = 1.469 at 1625 nm
- OFS TrueWave® REACH
 - n = 1.471 at 1310 nm
 - n = 1.470 at 1550 nm

1.3.3 Bandwidth

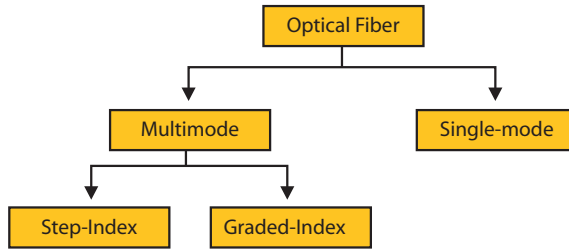
Bandwidth is defined as the width of the frequency range that can be transmitted by an optical fiber. The bandwidth determines the maximum transmitted information capacity of a channel, which can be carried along the fiber over a given distance. Bandwidth is expressed in MHz·km. In multimode fiber, bandwidth is mainly limited by modal dispersion; whereas almost no limitation exists for bandwidth in single-mode fiber.



Typical bandwidths for different types of fiber

1.4 Types of Fiber

Fiber is classified as either multimode or single-mode based on the way in which the light travels through it. The fiber type is closely related to the diameter of the core and cladding and how light travels through it.

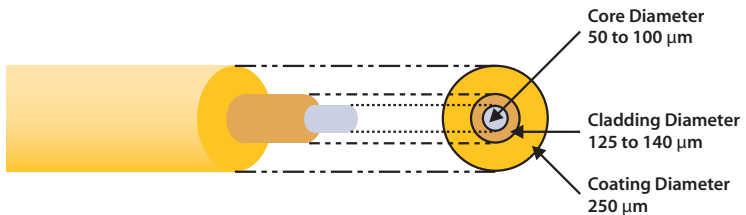


Types of glass fiber

1.4.1 Multimode Fiber

Multimode fiber, due to its large core, allows for the transmission of light using different paths (multiple modes) along the link, making multimode fiber quite sensitive to modal dispersion.

The primary advantages of multimode fiber are its ease of coupling to light sources and to other fiber, lower cost light sources (transmitters), and simplified connectorization and splicing processes. However, its relatively high attenuation and low bandwidth limit the transmission of light over multimode fiber to short distances.



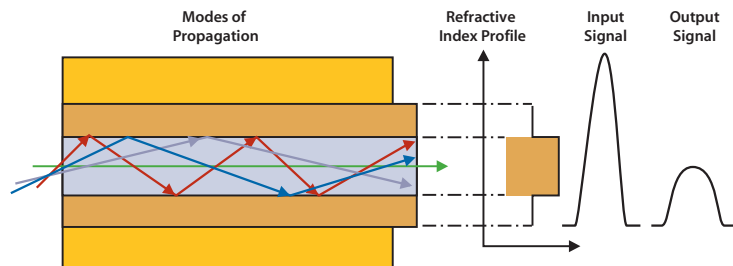
The composition of multimode fiber

1.4.1.1 Step-Index Multimode Fiber

Step-index (SI) multimode fiber guides light rays through total reflection on the boundary between the core and cladding. The refractive index is uniform in the core. SI multimode fiber has a minimum core diameter of 50 or 62.5 μm , a cladding diameter between 100 and 140 μm , and a numerical aperture between 0.2 and 0.5.

Due to modal dispersion, the drawback of SI multimode fiber is its very low bandwidth, which is expressed as the bandwidth-length product in $\text{MHz}\cdot\text{km}$. A fiber bandwidth of 20 $\text{MHz}\cdot\text{km}$ indicates that the fiber is suitable for carrying a 20 MHz signal for a distance of 1 km, a 10 MHz signal for a distance of 2 km, a 40 MHz signal for a distance of 0.5 km, and so on.

A plastic coating surrounds SI multimode fiber, which is used mostly for short distance links that can accommodate high attenuations.

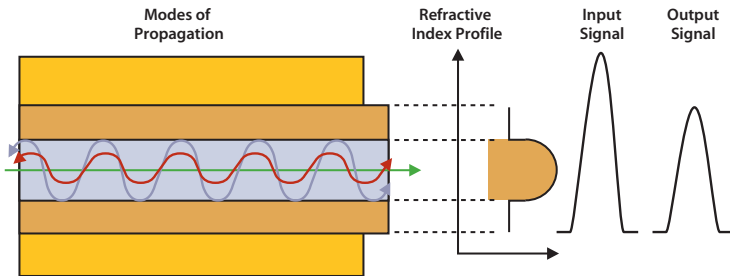


Light propagation through SI multimode fiber

1.4.1.2 Graded-Index Multimode Fiber

The core of graded-index (GI) multimode fiber possesses a non-uniform refractive index, decreasing gradually from the central axis to the cladding. This index variation of the core forces the rays of light to progress through the fiber in a sinusoidal manner.

The highest-order modes will have a longer path to travel, but outside of the central axis in areas of low index, their speeds will increase. In addition, the difference in speed between the highest-order modes and the lowest-order modes will be smaller for GI multimode fiber than for SI multimode fiber.



Light propagation through GI multimode fiber

Typical attenuations for GI multimode fiber:

- 3 dB/km at 850 nm
- 1 dB/km at 1300 nm

Typical numerical aperture for GI multimode fiber: 0.2

Typical bandwidth-length product for graded-index multimode fiber:

- 160 MHz·km at 850 nm
- 500 MHz·km at 1300 nm

Typical values for the refractive index:

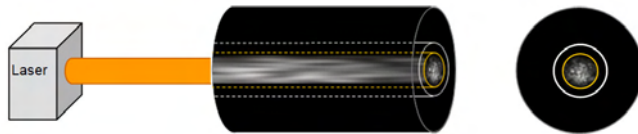
- 1.49 for 62.5 μm at 850 nm
- 1.475 for 50 μm at 850 nm and 1.465 for 50 μm at 1300 nm

1.4.1.3 Launch Conditions and Encircle Flux

Launch Conditions

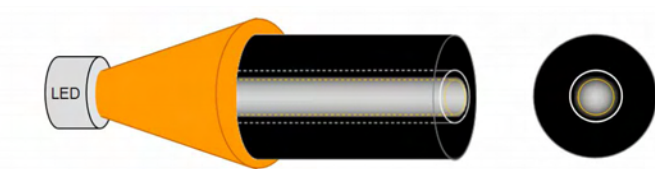
Launch conditions correspond to how optical power is launched into the fiber core when measuring fiber attenuation.

Ideal launch conditions should occur if the light is distributed through the whole fiber core. Actually, multimode optical fiber launch conditions may typically be characterized as being underfilled or overfilled.



Transmission of Light in Multimode Fiber in Underfilled Conditions

They are characterized as underfilled when most of the optical power is concentrated in the center of the fiber, which occurs when the launch spot size and angular distribution are smaller than the fiber core (for example when the source is a laser or vertical cavity surface-emitting laser [VCSEL]).



Transmission of Light in Multimode Fiber in Overfilled Conditions

An overfilled launch condition occurs when the launch spot size and angular distribution are larger than the fiber core (for example when the source is a light-emitting diode [LED]). Incident light that falls outside the fiber core is lost as well as light that is at angles greater than the angle of acceptance for the fiber core.

Light sources affect attenuation measurements such that one that underfills the fiber exhibits a lower attenuation value than the actual, whereas one that overfills the fiber exhibits a higher attenuation value than the actual.

Underfilled/Overfilled—What is the best?

Neither underfilled or overfilled is optimal, because both result in measurement variations.

Measurement variations are not critical when the allowed loss budget is over-dimensioned versus the expected bandwidth. But it becomes important to know the variation range in case of loss budget closed to its allowed limitations. In that case, a 50-percent variation may be too important to certify the network, thus requiring fine measurements.

The purpose of the International Electrotechnical Commission (IEC) 61280-4-1 is to provide guidance to guarantee that the variation in attenuation remains within ± 10 percent.

Using IEC 61280-4-1-compliant test equipment in the field ensures that attenuation measurements will vary less than ± 10 percent for >1 dB loss and ± 0.07 dB for <1 dB loss among various pieces of test equipment.

Encircled Flux

The new parameter covered in the IEC 61280-4-1 Ed2 standard from June 2009 is known as Encircled Flux (EF), which is related to distribution of power in the fiber core and also the launch spot size (radius) and angular distribution.

EF corresponds to the ratio between the transmitted power at a given radius of the fiber core and the total injected power. For example, the picture below illustrates the transmitted power at a radius of 15 μm (light blue). The EF value at 15 μm equals the ratio between the amount of light transmitted in that middle part and the total amount of light emitted into the whole core (yellow circle):

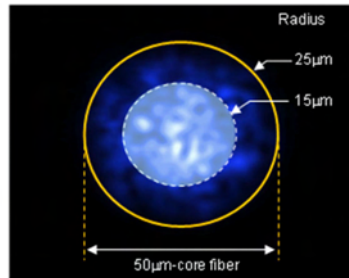
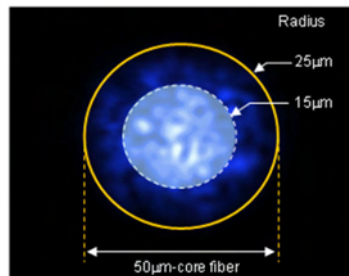


Illustration of EF value at 15 μm radius of a 50 μm -core Fiber

IEC 61280-4-1 Standard

The IEC 61280-4-1 standard recommendations are based on the defined lower and upper boundaries of EF values at four predefined radii of the fiber core (10, 15, 20, and 22 μm), and for each wavelength (850 and 1300 nm).



Illuminated core of a 50 μm -core

1.4.1.4 Types of Multimode Fiber

The International Telecommunications Union (ITU-T) G.651 and Institute of Electrical and Electronic Engineers (IEEE) 802.3 standards define the characteristics of a GI multimode optical fiber cable. The increased demand for bandwidth in multimode applications, including Gigabit Ethernet (GigE) and 10 GigE, has resulted in the definition of four different International Organization for Standardization (ISO) categories.

Comparing the ISO categories of the ITU-T G.651 standard

Standards	Characteristics	Wavelengths	Applications
G.651.1 ISO/IEC 11801:2002 (OM1) amd 2008	Legacy GI multimode fiber	850 and 1300 nm	Data communications in access networks
G.651.1 ISO/IEC 11801:2002 (OM2) amd 2008	Legacy GI multimode fiber	850 and 1300 nm	Video and data communications in access networks
G.651.1 ISO/IEC 11801:2002 (OM3) amd 2008	Laser optimized; GI multimode fiber; 50/125 μm maximum	Optimized for 850 nm	GigE and 10 GigE transmissions in local area networks (up to 300 m)
G.651.1 ISO/IEC 11801:2002 (OM4) amd 2008	VCSELs optimized	Optimized for 850 nm	40 and 100 Gbps transmissions in data centers

1.4.1.5 50 μm versus 62.5 μm Multimode Fibers

When optical transmission appeared in the field in the 1970s, optical links were based on 50 μm multimode fiber waveguides and LED light sources for both short and long ranges. In the 1980s, laser-powered single-mode fibers appeared and became the preferred choice for long distance, while multimode waveguides were positioned as the most cost-effective solution for local networks and for interconnecting building and campus backbones over distances of 300 to 2000 m.

A few years later, emerging applications in local networks required higher data rates including 10 Mbps, which pushed the introduction of 62.5 μm multimode fiber that could drive 10 Mbps over 2000 m because of its ability to capture more light power from the LED. At the same time, its higher numerical aperture eased the cabling operation and limited signal attenuation caused by cable stresses. These improvements made 62.5 μm multimode fiber the primary choice for short-range LANs, data centers, and campuses operating at 10 Mbps.

Today, Gigabit Ethernet (1 Gbps) is the standard and 10 Gbps is becoming more common in local networks. The 62.5 μm multimode fiber has reached its performance limits, supporting 10 Gbps over 26 m (maximum). These limitations hastened the recent deployment of a new design of economical lasers called VCSELs and of a small core of 50 μm fiber that is 850 nm laser-optimized.

Demand for increased data rates and greater bandwidth has further led to widespread use of 50 μm laser-optimized fibers capable of offering 2000-MHz \cdot km bandwidth and a high-speed data rate over long distance. Trends in local network design are to cable backbone segments with such fibers in order to build a more future-proof infrastructure.

1.4.1.6 Data Communication Rate and Transmission Lengths

When installing fiber cables, it is important to understand their capabilities in terms of bandwidth along the distance to ensure that installations are well-dimensioned and will support future needs.

As a first step, it is possible to estimate the transmission length according to the ISO/IEC 11801 standard table of recommended distances for networking Ethernet. This table assumes a continuous cable length without any devices, splices, connectors, or other loss factors that affect signal transmission.

Network Application (IEEE 802.3)	Nominal Transmission Wavelength	Maximum Channel Length (ISO/IEC 11801)	
		50 μm fiber	62.5 μm fiber
10BASE-SR/SW	850 nm	300 m	33 m
10BASE-LX4	1300 nm	300 m	300 m

As a second step, the cabling infrastructure should respect maximum channel attenuation to ensure a reliable signal transmission over distance. This attenuation value should consider end-to-end channel losses, including:

- The fiber attenuation profile, as it corresponds to 3.5 dB/km for multimode fibers at 850 nm and to 1.5 dB/km for multimode fibers at 1300 nm (according to ANSI/TIA-568-B.3 and ISO/IEC 11801 standards).
- Splices (typically up to 0.1 dB loss), connectors (typically up to 0.5 dB loss), and other commonly occurring losses.

Maximum channel attenuation is specified in the ANSI/TIA-568-B.1 standard as follows:

10 Gigabit Ethernet	Wavelength (nm)	Maximum Channel Attenuation (dB) According to ANSI/TIA-568-B.1			
		62.5 $\mu\text{m}^{(1)}$ MM	50 $\mu\text{m}^{(3)}$ MM	850 nm Laser-optimized 50 μm MM	9 μm SM
10GBASE-SX	850	2.5 ⁽²⁾	2.3 ⁽⁴⁾	2.6	–
10GBASE-LX4	1300	2.5	2.0 ⁽⁵⁾	2.0	6.6

(1) Application specifies 62.5 μm fiber with 200/500 MHz•km bandwidth at 850 nm

(2) 2.6 dB for fiber with 160/500 MHz•km modal bandwidth

(3) Application specifies 50 μm fiber with 500/500 MHz•km bandwidth at 850 nm

(4) 2.2 dB for fiber with 400/400 MHz•km modal bandwidth

(5) 2.0 dB for fiber with 400/400 MHz•km modal bandwidth

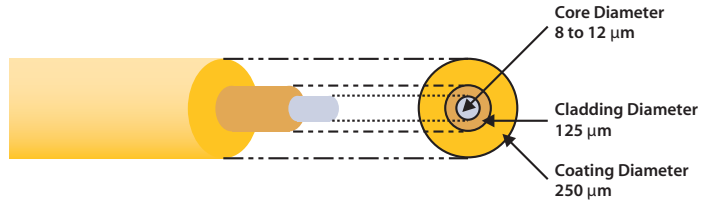
1.4.2 Single-mode Fiber

The advantage of single-mode fiber is its higher performance with respect to bandwidth and attenuation. The reduced core diameter of single-mode fiber limits the light to only one mode of propagation, eliminating modal dispersion completely.

With proper dispersion compensating components, a single-mode fiber can carry signals of 10 and 40 Gbps or above over long distances. The system carrying capacity may be further increased by injecting multiple signals of slightly differing wavelengths (wavelength division multiplexing) into one fiber.

The small core size of single-mode fiber generally requires more expensive light sources and alignment systems to achieve efficient coupling. In addition, splicing and connectorization are also somewhat complicated. Nonetheless, for high performance systems or for systems that are more than a few kilometers in length, single-mode fiber remains the best solution.

The typical dimensions of single-mode fiber range from a core of 8 to 12 μm and a cladding of 125 μm . The refractive index of single-mode fiber is typically 1.465.



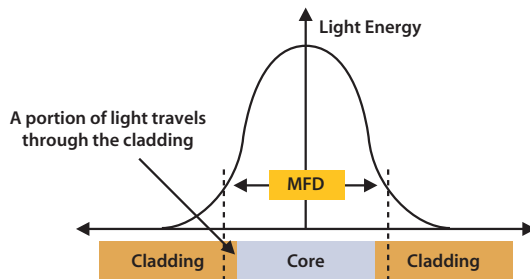
The composition of single-mode fiber

The small core diameter of single-mode fiber decreases the number of propagation modes, therefore, only one ray of light propagates down the core at a time.

1.4.2.1 Mode Field Diameter

The mode field diameter (MFD) of single-mode fiber can be expressed as the section of the fiber where the majority of the light energy passes.

The MFD is larger than the physical core diameter. That is, a fiber with a physical core of 8 μm can yield a 9.5 μm MFD. This phenomenon occurs because some of the light energy also travels through the cladding.

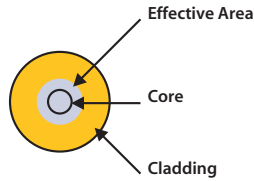


The MFD of single-mode fiber

Larger mode field diameters are less sensitive to lateral offset during splicing, but they are more sensitive to losses incurred by bending during either the installation or cabling processes.

Effective Area

Effective area is another term that is used to define the mode field diameter. The effective area is the area of the fiber corresponding to the mode field diameter.



The effective area of single-mode fiber

The effective area (or mode field diameter) directly influences nonlinear effects, which depend directly on the power density of the light injected into the fiber. The higher the power density the higher the incidence of nonlinear effects.

The effective area of a fiber determines the power density of the light. For a given power level, a small effective area will provide a high power density. Subsequently, for a larger effective area, the power is better distributed, and the power density is less important. In other words, the smaller the effective area, the higher the incidence of nonlinear effects.

The effective area of a standard single-mode fiber is approximately $80 \mu\text{m}^2$ and can be as low as $30 \mu\text{m}^2$ for compensating fiber. The effective area of a fiber is often included in the description of the fiber's name, such as Corning's LEAF (for large effective area fiber).

1.4.2.2 Types of Single-mode Fiber

There are different types of single-mode fiber, which are classified according to their attenuation range, chromatic dispersion (CD) values, and polarization mode dispersion (PMD) coefficients. The ITU-T has provided a set of standards in order to classify single-mode fiber.

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

	Characteristics	Wavelength Coverage	Applications
G.652.A	Max PMD = $0.5 \text{ ps}/\sqrt{\text{km}}$	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 Gbps up to 40 km (Ethernet), and STM-256 for G.693.
G.652.B	Maximum attenuation specified at 1625 nm. Max PMD = $0.2 \text{ ps}/\sqrt{\text{km}}$	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). Max PMD = $0.5 \text{ ps}/\sqrt{\text{km}}$	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). Max PMD = $0.2 \text{ ps}/\sqrt{\text{km}}$	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.

G.653: Characteristics of dispersion-shifted single-mode optical fiber and cable

	Characteristics	Wavelength Coverage	Applications
G.653.A	Zero chromatic dispersion value at 1550 nm. Maximum attenuation of $0.35 \text{ dB}/\text{km}$ at 1550 nm. Max PMD = $0.5 \text{ ps}/\sqrt{\text{km}}$	1550 nm	Supports high bit rate applications at 1550 nm over long distances.
G.653.B	Same as G.653.A, except: Max PMD = $0.2 \text{ ps}/\sqrt{\text{km}}$	1550 nm	Introduced in 2003 with a low PMD coefficient, this standard supports higher bit rate transmission applications than G.653.

G.655: Characteristics of non-zero dispersion-shifted single-mode optical fiber and cable

	Characteristics	Wavelength Coverage	Applications
G.655.A	Maximum attenuation specified at 1550 nm only. Lower CD value than G.655.B and G.655.C. Max PMD = $0.5 \text{ ps}/\sqrt{\text{km}}$	C bands	Supports DWDM transmission (G.692) applications in the C bands with down to 200 GHz channel spacing.
G.655.B	Maximum attenuation specified at 1550 and 1625 nm. Higher CD value than G.655.A. Max PMD = $0.5 \text{ ps}/\sqrt{\text{km}}$	1550 and 1625 nm regions (C+L bands)	Supports DWDM transmission (G.692) applications in the C+L bands with down to 100 GHz channel spacing.
G.655.C	Maximum attenuation specified at 1550 and 1625 nm. Higher CD value than G.655.A. Max PMD = $0.2 \text{ ps}/\sqrt{\text{km}}$	From O to C bands	Similar to G.655.B, but this standard allows for transmission applications at high bit rates for STM-64/OC-192 (10 Gbps) over longer distances. Also suitable for STM-256/OC-568 (40 Gbps).

The recent G.656 standard (06/2004) is an extension of G.655, but it specifically addresses the wider wavelength range for transmission over the S, C, and L bands.

G.656: Characteristics of non-zero dispersion shifted fiber for wideband transport

	Characteristics	Wavelength Coverage	Applications
G.656	Maximum attenuation specified at 1460, 1550, and 1625 nm. Minimum CD value of 2 ps/nm·km between 1460 and 1625 nm. Max PMD = 0.2 ps/√km	S, C, and L bands	Supports both CWDM and DWDM systems throughout the wavelength range of 1460 and 1625 nm.

G.657: Characteristics of a bending loss insensitive single-mode fiber for access network

	Characteristics	Wavelength Coverage	Applications
G.657.A	At 15 mm radius, 10 turns, 0.25 dB max at 1550 nm, 1 dB max at 1625 nm	Wideband coverage (from 0 to L bands)	Optimized access installation with respect to macro bending, loss, others parameters being like G.652D
G.657.B	At 15 mm radius, 10 turns, 0.03 dB max at 1550 nm, 0.1 dB max at 1625 nm	Wideband coverage (from 0 to L bands)	Optimized access installation with very short bending radii

Other types of fiber exist, such as polarization maintaining single-mode fiber and plastic fiber, which are outside the scope of this document.

1.4.3 Review of Single-mode and Multimode Fiber

The following table provides a quick comparison between multimode and single-mode fiber.

Review of single-mode and multimode fiber

	Multimode	Single-mode
Cost of fiber	Expensive	Less expensive
Transmission equipment	Basic and low cost (LED)	More expensive (laser diode)
Attenuation	High	Low
Transmission wavelengths	850 to 1300 nm	1260 to 1650 nm
Use	Larger core, easier to handle	Connections more complex
Distances	Local networks (< 2 km)	Access/medium/long haul networks (> 200 km)
Bandwidth	Limited bandwidth (100G over very short distances)	Nearly infinite bandwidth (> 1 Tbps for DWDM)
Conclusion	The fiber is more costly, but network deployment is relatively inexpensive.	Provides higher performance, but building the network is expensive.

1.5 Light Transmission

Light transmission in optical fiber uses three basic elements: a transmitter, a receiver, and a transmission medium that passes the signal from one to the other. The use of optical fiber introduces attenuation and dispersion into the system. Attenuation tends to increase the power requirements of the transmitter in order to meet the power requirements of the receiver. Dispersion, on the other hand, limits the bandwidth of the data that can be transmitted over the fiber.

1.5.1 Attenuation

As the light signal traverses the fiber, it decreases in power level. The decrease in power level is expressed in decibels (dB) or as a rate of loss per unit distance (dB/km).

1.5.1.1 Fiber Spectral Attenuation

The two main loss mechanisms of light transmission in optical fiber are light absorption and scattering.

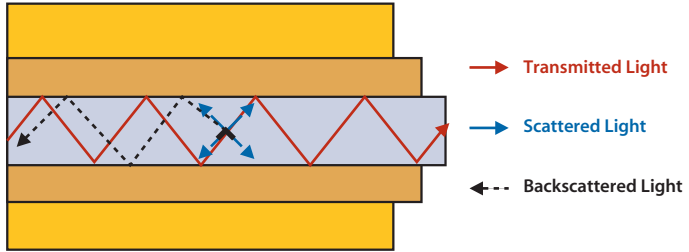
Light Absorption

Light is absorbed in the fiber material as its energy is converted to heat due to molecular resonance and wavelength impurities. For example, hydrogen and hydroxide resonance occurs at approximately 1244 and 1383 nm.

Rayleigh Scattering

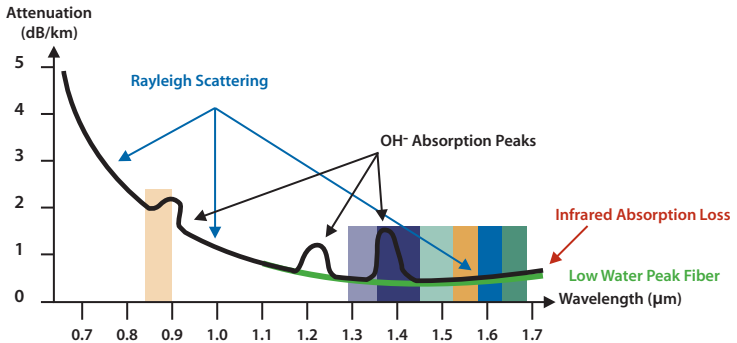
Scattering, primarily Rayleigh scattering, also contributes to attenuation. Scattering causes dispersion of the light energy in all directions, with some of the light escaping the fiber core. A small portion of this light energy is returned down the core and is termed backscattering.

Forward light scattering (Raman scattering) and backward light scattering (Brillouin scattering) are two additional scattering phenomena that can occur in optical materials under high power conditions.



Backscattering effects of light transmission

Attenuation depends on the fiber type and the wavelength. For example, Rayleigh scattering is inversely proportional to the fourth power of the wavelength. If the absorption spectrum of a fiber is plotted against the wavelength of the laser, certain characteristics of the fiber can be identified. The following graph illustrates the relationship between the wavelength of the injected light and the total fiber attenuation.



Fiber attenuation as a function of wavelength

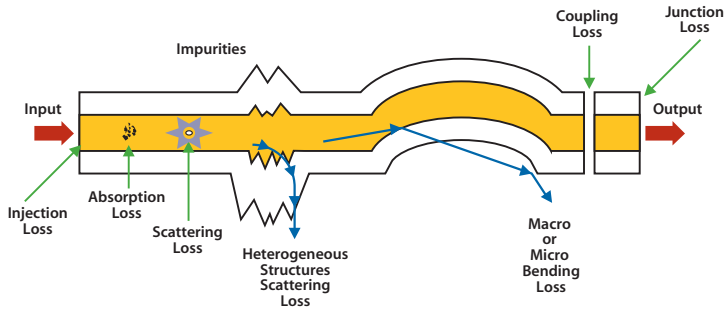
The main telecommunication transmission wavelengths correspond to the points on the graph where attenuation is at a minimum. These wavelengths are known as the telecom windows. The ITU-T G.692 standard has defined additional windows, called bands, which are dedicated to dense wavelength division multiplexing (DWDM) transmission systems.

■ 820 – 880 nm (1st window)	■ S Band 1460 – 1530 nm
■ O Band 1260 – 1360 nm (2nd window)	■ C Band 1530 – 1565 nm (3rd window)
■ E Band 1360 – 1460 nm	■ L Band 1565 – 1625 nm
	■ U Band 1625 – 1675 nm

The OH- symbol identified in the graph indicates that at the wavelengths of 950, 1244, and 1383 nm, the presence of hydrogen and hydroxide ions in the fiber optic cable material causes an increase in attenuation. These ions result from the presence of water that enters the cable material through either a chemical reaction in the manufacturing process or as humidity in the environment. The variation of attenuation with wavelength due to the water peak for standard single-mode fiber optic cable occurs mainly around 1383 nm. Recent advances in the manufacturing processes of fiber optic cable have overcome the 1383 nm water peak and have resulted in low water peak fiber. Examples of this type of fiber include SMF-28e from Corning and OFS AllWave from Lucent.

1.5.1.2 Link Loss Mechanisms

For a fiber optic span, the effects of passive components and connection losses must be added to the inherent attenuation of the fiber in order to obtain the total signal attenuation. This attenuation (or loss), for a given wavelength, is defined as the ratio between the input power and the output power of the fiber being measured. It is generally expressed in decibels (dB).



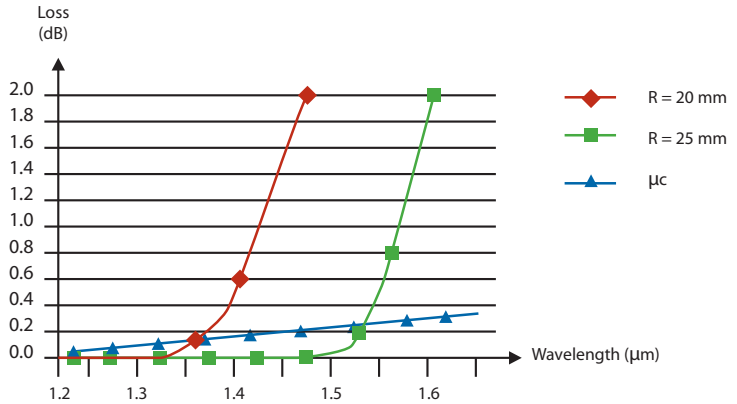
Link loss mechanisms

1.5.1.3 Micro Bends and Macro Bends

Micro bends and macro bends are common problems in installed cable systems because they can induce signal power loss.

Micro bending occurs when the fiber core deviates from the axis and can be caused by manufacturing defects, mechanical constraints during the fiber laying process, and environmental variations (temperature, humidity, or pressure) during the fiber's lifetime. The trace "µc" refers to a fiber having micro bending.

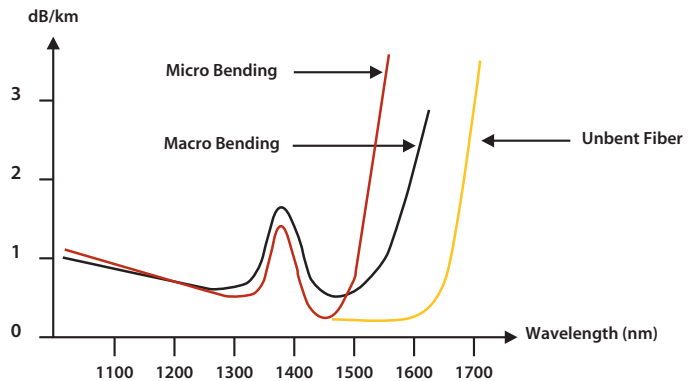
Macro bending refers to a large bend in the fiber (with more than a 2 mm radius). The graph below shows the influence of the bend radius (R) on signal loss as a function of the wavelength.



The effects of micro and macro bending on a fiber

For example, the signal loss for a fiber that has a 25 mm macro bend radius will be 2 dB at 1625 nm, but only 0.4 dB at 1550 nm.

Another way of calculating the signal loss is to add the typical fiber attenuation coefficient (according to the specific wavelength as indicated below) to the bending loss.

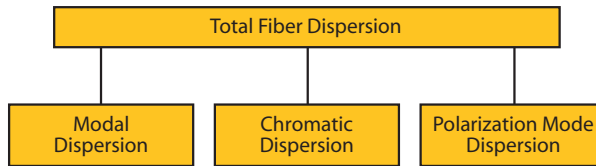


Typical attenuation coefficients for bent and unbent fiber

As shown in the above graph, if the L band (1565 – 1625 nm) or the U band (1625 – 1675 nm) is utilized, then loss testing is necessary at transmission wavelengths up to the upper limit of the band. For this reason, new test equipment has been developed with 1625 nm testing capabilities. The most important fiber parameters for network installation are splice loss, link loss, and optical return loss (ORL), therefore, it is necessary to acquire and use the appropriate test equipment.

1.5.2 Dispersion

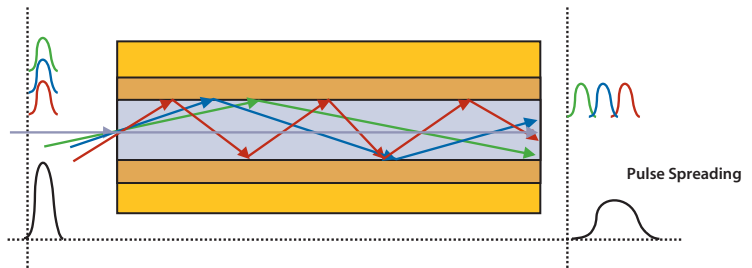
Another factor that affects the signal during transmission is dispersion, which reduces the effective bandwidth available for transmission. Three main types of dispersion exist: modal dispersion, chromatic dispersion, and polarization mode dispersion.



Types of fiber dispersion

1.5.2.1 Modal Dispersion

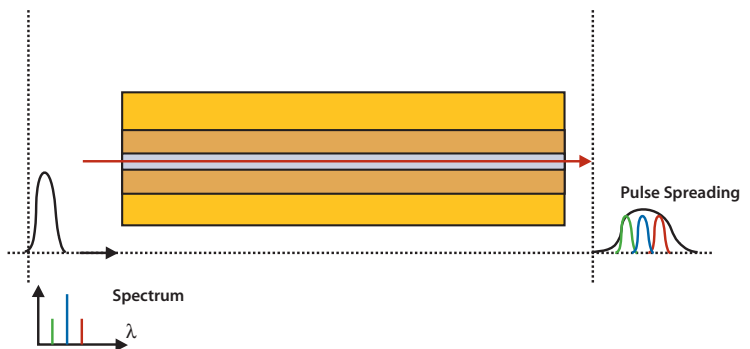
Modal dispersion typically occurs with multimode fiber. When a very short light pulse is injected into the fiber within the numerical aperture, all of the energy does not reach the end of the fiber simultaneously. Different modes of oscillation carry the energy down the fiber using paths of differing lengths. For example, multimode fiber with a 50 μm core may have several hundred modes. This pulse spreading by virtue of different light path lengths is called modal dispersion, or more simply, multimode dispersion.



Modal dispersion in SI multimode fiber

1.5.2.2 Chromatic Dispersion

Chromatic dispersion (CD) occurs because a light pulse is made up of different wavelengths, each traveling at different speeds down the fiber. These different propagation speeds broaden the light pulse when it arrives at the receiver, reducing the signal-to-noise ratio (SNR) and increasing bit errors.



CD caused by different wavelengths in a light source

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

- 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).

Both the dispersion coefficient (standardized to one kilometer) and the slope are dependent on the length of the fiber.

CD primarily depends on the manufacturing process. Cable manufacturers consider the effects of CD when designing different types of fiber for different applications and different needs, such as standard fiber, dispersion shifted fiber, or non-zero dispersion shifted fiber.

1.5.2.3 Polarization Mode Dispersion

Polarization mode dispersion (PMD) is a basic property of single-mode fiber that affects the magnitude of the transmission rate. PMD results from the difference in propagation speeds of the energy of a given wavelength, which is split into two polarization axes perpendicular to each other (as shown in the diagram below). The main causes of PMD are non-circularities of the fiber design and externally applied stresses on the fiber (macro bending, micro bending, twisting, and temperature variations).



PMD (or differential group delay) effects on a fiber

The PMD is also referred to as the mean value of all differential group delays (DGD) and is expressed in picoseconds (ps). It can also be stated as the PMD coefficient, which is related to the square root of the distance and is expressed in $\text{ps}/\sqrt{\text{km}}$.

The PMD (mean DGD) causes the transmission pulse to broaden when it is transmitted along the fiber. This phenomenon generates distortion, increasing the bit error rate (BER) of the optical system. The consequence of PMD is that it limits the transmission bit rate on a link. Therefore, it is important to know the PMD value of the fiber in order to calculate the bit rate limits of the fiber optic link.

1.5.3 Optical Return Loss

1.5.3.1 Definition

ORL represents the total accumulated light power reflected back to the source from the complete optical span, which includes the backscattering light from the fiber itself as well as the reflected light from all of the joints and terminations. ORL, expressed in decibels (dB), is defined as the logarithmic ratio of the incident power to the reflected power at the fiber origin.

$$\text{ORL} = 10 \text{Log} \frac{P_e}{P_r} \quad (\geq 0)$$

Where P_0 is the emitted power and P_r the reflected power, expressed in Watt (W)

A high level of ORL will decrease the performance of some transmission systems. For example, high backreflection can dramatically affect the quality of an analog video signal, resulting in the degradation of the video image quality.

The higher the ORL value the lower the reflected power and, subsequently, the smaller the effect of the reflection. Therefore, an ORL value of 40 dB is more desirable than an ORL value of 30 dB. It is important to note that ORL is expressed as a positive decibel value whereas the reflectance of a connector is expressed as negative value.

1.5.3.2 The Distance or Attenuation Effect

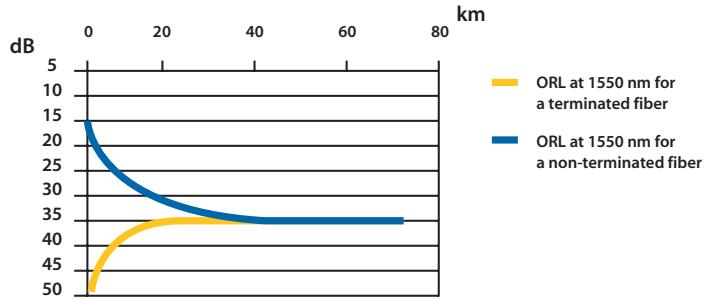
The reflectance value of the event as well as its distance from the transmitter terminal both affect the total ORL value.

As the length of the fiber increases, the amount of total backscattered light by the fiber also increases, and the fiber end reflection decreases. Therefore, for a short fiber link without intermediate reflective events, fiber end reflection is the predominate contribution to the total ORL as the amount of reflected light is not highly attenuated by the fiber.

On the other hand, end reflection of a long fiber length or a highly attenuated link is attenuated by absorption and scatter effects. In this case, the backscattered light becomes the major contribution to the total ORL, limiting the effect of end reflection.

The following graph shows the total ORL (reflectance and backscatter) for both terminated fiber (with no end reflection) and non-terminated fiber (with a glass-to-air backreflection of 4 percent or -14 dB). For distances shorter than 40 km, the difference in ORL between the terminated and non-terminated fiber is significant.

But for longer distances (higher losses), the total ORL is nearly equal.



ORL as a function of distance at 1550 nm for terminated and non-terminated fiber

The importance of reflective events on total ORL depends, not only on their location along the fiber link, but also on the distance between the reflection and the active transmission equipment.

1.5.3.3 Effects of High ORL Values

If the ORL value is too high (low dB value), then light can resonate in the cavity of the laser diode, causing instability. Several different effects can result from high ORL values:

- Increased transmitter noise reducing optical signal-to-noise ratio (OSNR) in analog video transmission (CATV) systems and increasing BER in digital transmission systems
- Increase light source interference changing the laser's central wavelength and varying the output power
- Higher incidence of transmitter damage

Solutions are available that allow for a reduction in ORL value or that limit the undesirable effects associated with a high ORL value include:

- Use of low-reflection connectors, such as 8° angled polished contacts (APC); high return loss (HRL) connectors; or ultra polished contacts (UPC)
- Use of optical isolators near the laser in order to reduce back-reflection levels

1.5.4 Nonlinear Effects

High power level and small effective area of the fiber mainly cause nonlinear effects. With an increase in the power level and the number of optical channels, nonlinear effects can become problematic factors in transmission systems. These analog effects can be divided into two categories:

1. Refractive index phenomena causes phase modulation through variations in the refractive indexes:
 - Self-phase modulation (SPM)
 - Cross-phase modulation (XPM)
 - Four-wave mixing (FWM)
2. Stimulated scattering phenomena leads to power loss:
 - Stimulated Raman scattering (SRS)
 - Stimulated Brillouin scattering (SBS)

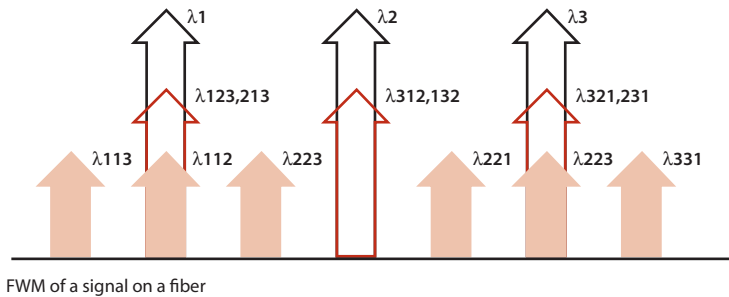
1.5.4.1 Refractive Index Phenomena

Nonlinear effects are dependent upon the nonlinear portion of the refractive index n and cause the refractive index to increase for high signal power levels. Behind an erbium doped fiber amplifier (EDFA), the high output can create nonlinear effects, such as FWM, SPM, and XPM.

Four-Wave Mixing

FWM is an interference phenomenon that produces unwanted signals from three signal frequencies ($\lambda_{123} = \lambda_1 + \lambda_2 - \lambda_3$) known as ghost channels that occur when three different channels induce a fourth channel.

A number of ways exist in which channels can combine to form a new channel according to the above formula. In addition, note that just two channels alone can also induce a third channel.



Due to high power levels, FWM effects produce a number of ghost channels (some of which overlap actual signal channels), depending on the number of actual signal channels. For example, a 4-channel system will produce 24 unwanted ghost channels and a 16-channel system will produce 1920 unwanted ghost channels. Therefore, FWM is one of the most adverse nonlinear effects in DWDM systems.

In systems using dispersion-shifted fiber, FWM becomes a tremendous problem when transmitting around 1550 nm or the zero dispersion wavelength. Different wavelengths traveling at the same speed, or group velocity, and at a constant phase over a long period of time will increase the effects of FWM. In standard fiber (non-dispersion-shifted fiber), a certain amount of CD occurs around 1550 nm, leading to different wavelengths having different group velocities, reducing the FWM effects. Using irregular channel spacing can also achieve a reduction in FWM effects.

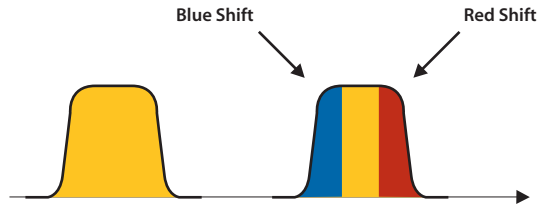
Self-Phase Modulation

SPM is the effect that a signal has on its own phase, resulting in signal spreading. With high signal intensities, the light itself induces local variable changes in the refractive index of the fiber known as the Kerr effect. This phenomenon produces a time-varying phase in the same channel. The time-varying refractive index modulates the phase of the transmitted wavelength(s), broadening the wavelength spectrum of the transmitted optical pulse.

Where L is the link distance, S is the fiber section, and P is the optical power.

$$\Delta\phi = \frac{2\pi}{\lambda} \times \frac{L}{S \times P}$$

The result is a shift toward shorter wavelengths at the trailing edge of the signal (blue shift) as well as a shift toward longer wavelengths at the leading edge of the signal (red shift).



SPM of a signal on a fiber

The wavelength shifts that SPM causes are the exact opposite of positive CD. In advanced network designs, SPM can be used to partly compensate for the effects of CD.

Cross Phase Modulation

XPM is the effect that a signal in one channel has on the phase of another signal. Similar to SPM, XPM occurs as a result of the Kerr effect. However, XPM effects only arise when transmitting multiple channels on the same fiber. In XPM, the same frequency shifts at the edges of the signal in the modulated channel occur as in SPM, spectrally broadening the signal pulse.

1.5.4.2 Scattering Phenomena

Scattering phenomena can be categorized according to the processes that occur when the laser signal is scattered by fiber molecular vibrations (optical photons) or by induced virtual grating.

Stimulated Raman Scattering

SRS is an effect that transfers power from a signal at a shorter wavelength to a signal at a longer wavelength. The interaction of signal light waves with vibrating molecules (optical photons) within the silica fiber causes SRS, thus scattering light in all directions. Wavelength differences between two signals of about 100 nm (13.2 THz), 1550 to 1650 nm for example, show maximum SRS effects.

Stimulated Brillouin Scattering

SBS is a backscattering phenomenon that causes loss of power. With high-power signals, the light waves induce periodic changes in the refractive index of the fiber, which can be described as induced virtual grating that travels away from the signal as an acoustic wave. The signal itself is then scattered, but it is mostly reflected off this induced virtual grating. SBS effects occur when transmitting only a few channels.

1.5.5 Summary of Transmission Effects

The following table summarizes the different fiber transmission phenomenon and their associated impairments in optical telecommunication systems.

Summary of transmission effects

Impairment	Causes	Critical Power per Channel	Effects	Compensation
Attenuation	Material absorption/system		<ul style="list-style-type: none"> • Reduced signal power levels • Increased bit errors 	Shorter spans; purer fiber material
Chromatic Dispersion (CD)	Wavelength-dependent group velocity		<ul style="list-style-type: none"> • Increased bit errors 	Use of compensation fiber or modules (DCF/DCM)
Polarization Mode Dispersion (PMD)	Polarization state-dependent differential group delay		<ul style="list-style-type: none"> • Increased bit errors 	New fiber with low PMD values; careful fiber laying; PMD compensators
Four Wave Mixing (FWM)	Signal interference	10 mW	<ul style="list-style-type: none"> • Power transfer from original signal to other frequencies • Production of sidebands (harmonics) • Channel crosstalk • Increased bit errors 	Use of fiber with CD compensators; unequal channel spacing
Self Phase Modulation (SPM) and Cross Phase Modulation (XPM)	Intensity-dependent refractive index	10 mW	<ul style="list-style-type: none"> • Spectral broadening • Initial pulse compression (in positive CD regimes) • Accelerated pulse broadening (in negative CD regimes) • Channel crosstalk due to "walk-off" effects • Increased bit errors 	Use of fiber with CD compensators
Stimulated Raman Scattering (SRS)	Interaction of signal with fiber molecular structure	1 mW	<ul style="list-style-type: none"> • Decreased peak power • Decreased OSNR • Optical crosstalk (especially in bidirectional WDM systems) • Increased bit errors 	Careful power design
Stimulated Brillouin Scattering (SBS)	Interaction of signal with acoustic waves	5 mW	<ul style="list-style-type: none"> • Signal instability • Decreased peak power • Decreased OSNR • Optical crosstalk (especially in bidirectional WDM systems) • Increased bit errors 	Spectral broadening of the light source

1.6 Standards and Recommendations for Fiber Optic Systems

Many international and national standards govern optical cable characteristics and measurement methods. Some are listed below, but the list is not exhaustive. Releases are subject to change.


1.6.1 International Standards

Two main groups are working on international standards: the IEC and the ITU.

1.6.1.1 International Electrotechnical Commission

The IEC is a global organization that prepares and publishes international standards for all electrical, electronic, and related technologies, which serve as a basis for national standardization.

The IEC is composed of technical committees who prepare technical documents on specific subjects within the scope of an application in order to define the related standards. For example, the technical committee TC86 is dedicated to fiber optics, and its subcommittees SC86A, SC86B, and SC86C focus on specific subjects such as:

- SC86A: Fibers and Cables
 - SC86B: Fiber Optic Interconnecting Devices and Passive Components
 - SC86C: Fiber Optic Systems and Active Devices
-
- 

1.6.1.2 International Telecommunication Union

The ITU is an international organization that defines guidelines, technical characteristics, and specifications of telecommunications systems, networks, and services. It includes optical fiber performance and test and measurement applications and consists of three different sectors:

- Radiocommunication Sector (ITU-R)
- Telecommunication Standardization Sector (ITU-T)
- Telecommunication Development Sector (ITU-D)

1.6.2 National Standards

In addition to the international standards, countries or union of countries define their own standards in order to customize or fine tune the requirements to the specificity of their country.

1.6.2.1 European Telecommunications Standards Institute

The European Telecommunications Standards Institute (ETSI) defines telecommunications standards and is responsible for the standardization of Information and Communication Technologies (ICT) within Europe. These technologies include telecommunications, broadcasting, and their related technologies, such as intelligent transportation and medical electronics.

1.6.2.2 Telecommunication Industries Association/ Electronic Industries Alliance

The Telecommunication Industries Association (TIA) provides additional recommendations for the United States. TIA is accredited by the American National Standards Institute (ANSI) to develop industry standards for a wide variety of telecommunications products. The committees and subcommittees define standards for fiber optics, user premises equipment, network equipment, wireless communications, and satellite communications.

It is important to note that many other standard organizations exist in other countries.

1.6.3 Fiber Optic Standards

- IEC 61300-3-35: Fibre Optic Connector End Face Visual Inspection
- IEC 60793-1 and -2: Optical Fibers (includes several parts)
- IEC 60794-1, -2, and -3: Optical Fiber Cables
- G.651: Characteristics of 50/125 μm Multimode Graded-index Optical Fiber
- G.652: Characteristics of Single-mode Optical Fiber and Cable
- G.653: Characteristics of Single-mode Dispersion Shifted Optical Fiber and Cable
- G.654: Characteristics of Cut-off Shifted Single-mode Optical Fiber and Cable
- G.655: Characteristics of Non-zero Dispersion Shifted Single-mode Optical Fiber and Cable
- G.656: Characteristics of Non-zero Dispersion Shifted Fiber for Wideband Transport
- G.657: Characteristics of a Bending Loss Insensitive Single-mode Fiber for Access Networks

1.6.4 Test and Measurement Standards


1.6.4.1 Generic Test Standards

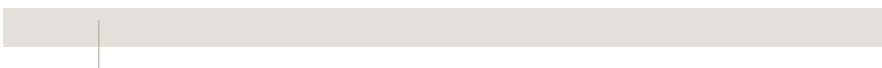
- IEC 61350: Power Meter Calibration
- IEC 61746: OTDR Calibration
- G.650.1: Definition and Test Methods for Linear, Deterministic Attributes of Single-mode Fiber and Cable
- G.650.2: Definition and Test Methods for Statistical and Non-linear Attributes of Single-mode Fiber and Cable

1.6.4.2 PMD Test Standards

- G.650.2: Definition and Test Methods for Statistical and Non-linear Attributes of Single-mode Fiber and Cable
- IEC 60793 1-48: Optical Fibers—Part 1-48: Measurement Methods and Test Procedures—Polarization Mode Dispersion
- IEC/TS 61941: Technical Specifications for Polarization Mode Dispersion Measurement Techniques for Single-mode Optical Fiber
- IEC 61280-3/TIA/TR-1029: Calculation of Polarization
- TIA 455 FOTP-124A: Polarization Mode Dispersion Measurement for Single-mode Optical Fiber and Cable Assemblies by Interferometry
- TIA 455 FOTP-113: Polarization Mode Dispersion Measurement of Single-mode Optical Fiber by the Fixed Analyzer Method
- TIA 455 FOTP-122A: Polarization Mode Dispersion Measurement for Single-mode Optical Fiber by the Stokes Parameter Method
- TIA TSB-107: Guidelines for the Statistical Specification of Polarization Mode Dispersion on Optical Fiber Cables
- TIA 455-196: Guidelines for Polarization Mode Measurements in Single-mode Fiber Optic Components and Devices
- GR-2947-CORE: Generic Requirements for Portable Polarization Mode Dispersion (PMD) Test Sets
- IEC 61280-4-4: Polarization Mode Dispersion Measurement for Installed Links
- TIA 445 FOTP-243: Polarization Mode Dispersion Measurement for Installed Single-mode Optical Fibers by Wavelength-scanning OTDR and State of Polarization Analysis

1.6.4.3 CD Test Standards

- G.650.1: Definition and Test Methods for Linear, Deterministic Attributes of Single-mode Fiber and Cable
 - IEC 60793 1-42: Optical Fibers—Part 1-42: Measurement Methods and Test Procedures—Chromatic Dispersion
 - IEC 61744: Calibration of Fiber Optic Chromatic Dispersion Test Sets
 - TIA/EIA FOTP-175-B: Chromatic Dispersion Measurement of Single-mode Optical Fibers
 - GR-761-CORE: Generic Criteria for Chromatic Dispersion Test Sets
 - GR-2854-CORE: Generic Requirements for Fiber Optic Dispersion Compensators
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Insertion Loss, Return Loss, Fiber Characterization, and Ancillary Test Kits

Chapter 2



2.1 Optical Fiber Testing

When analyzing a fiber optic cable over its product lifetime, performing a series of measurements will ensure its integrity.

- Mechanical tests
- Geometrical tests
- Optical tests
- Transmission tests

Perform the first three sets of measurements once as minor variations occur for these parameters during the fiber's lifetime. Perform several measurements on optical fiber or cables in order to characterize them before their use in signal transmission, many of which are described in the Fiber Optic Test Procedure (FOTP) propositions of the Telecommunication Industries Association (TIA) and are defined in the International Telecommunication Union's (ITU-T) G650 recommendations or in the EN 188 000 document.

Optical fiber testing

Mechanical Tests	Geometrical Tests	Optical Tests	Transmission Tests
Traction	Concentricity	Index profile	Bandwidth
Torsion	Cylindricity	Numerical aperture	Optical power
Bending	Core diameter	Spot size	Optical loss
Temperature	Cladding diameter		Optical return loss
			Reflectometry
			Chromatic dispersion
			Polarization mode dispersion
			Attenuation profile

2.2 Transmission Tests

In order to ensure proper light propagation and error-free transmission in an optical fiber network, optical parameters and limits have to be measured at different stage of the network life cycle.

2.2.1 Measurement Units

The decibel (dB) is often used to quantify the gain or loss of optical power for fiber or network elements. The number of decibels is equivalent to 10 times the logarithm of the power variation, which is the ratio between two power levels (expressed in watts [W]).

$$\text{dB} = 10 \text{ Log } \frac{P_1}{P_2}$$

The decibel is also often used in the context of transmitted signals and noise (lasers or amplifiers). Some of the most frequently used specifications include:

- dBm refers to the number of decibels relative to a reference power of 1 mW, which is often used to specify absolute power levels. Therefore, the equation above becomes:

$$P(\text{dBm}) = 10 \text{ Log } \frac{P_1}{1 \text{ mW}}$$

Where P_1 is expressed in mW.

- dBc refers to the number of decibels relative to a carrier and is used to specify the power of a sideband in a modulated signal relative to the carrier. For example, -30 dBc indicates that the sideband is 30 dB below the carrier.
- dBr refers to the number of decibels relative to a reference level and is used to specify the power variation according to a reference power level.

Power loss can then be calculated as the difference between two power levels (output and input) expressed in decibels.

$$\text{Loss (dB)} = P_{\text{out}} - P_{\text{in}}$$

The following table provides a set of absolute power levels converted from watts to dBm.

Comparing absolute power levels in watts and dBm

Absolute Power	Absolute Power
1 W	+30 dBm
100 mW	+20 dBm
10 mW	+10 dBm
5 mW	+7 dBm
1 mW	0 dBm
500 μ W	-3 dBm
100 μ W	-10 dBm
10 μ W	-20 dBm
1 μ W	-30 dBm
100 nW	-40 dBm

The following table provides the relationship between decibels and power loss in terms of a percentage.

Comparing loss (dB) and the percentage of power loss

Loss	Power Loss
-0.10 dB	2%
-0.20 dB	5%
-0.35 dB	8%
-1 dB	20%
-3 dB	50%
-6 dB	75%
-10 dB	90%
-20 dB	99%

2.2.2 Measurement Parameters

In order to qualify the use of an optical fiber or an optical fiber system for proper transmission, perform these several key measurements.

- End-to-end optical link loss
- Rate of attenuation per unit length
- Attenuation contribution to splices, connectors, and couplers (events)
- Length of the fiber or distance to an event
- Linearity of fiber loss per unit length (attenuation discontinuities)
- Reflectance or optical return loss (ORL)
- Chromatic dispersion (CD)
- Polarization mode dispersion (PMD)
- Attenuation profile (AP)

Other measurements, such as bandwidth, may also be performed. Except for a few specific applications, these other measurements are often less important.

Some measurements require access to both ends of the fiber. Others require access to only one end. Measurement techniques that require access to only one end are particularly interesting for field applications as these measurements reduce the time spent traveling from one end of the fiber cable system to the other. Field testing of optical cables requires testing at three levels: installation, maintenance, and restoration.

2.2.3 Field Testing

The following subsections provide a non-exhaustive list of the various tests to perform during each level of field testing. The exact nature of a testing program depends on the system design, the system criticality, and the contractual relationship between the cable and components suppliers, system owner, system installer, and system user.

2.2.3.1 Installation Tests

Pre-Installation Tests

Prior to installation, perform fiber inspections to ensure that the fiber cables received from the manufacturer conform to the required specifications (for example, connector end face condition, length, and attenuation) and have not been damaged during transit or cable placement.

Installation and Commissioning Tests

During installation and commissioning, perform tests to determine the quality of cable splices and terminations (connector end face condition, attenuation, location, and reflectance). Also perform tests to determine that the completed cable subsystem is suitable for the intended transmission system (end-to-end loss and system optical return loss). All of these tests provide a complete set of documentation of the cable link for maintenance purposes.

2.2.3.2 Maintenance Tests

Maintenance testing involves periodic evaluation of the cable system to ensure that no degradation of the cable, splices, or connections has occurred. Tests include cable attenuation as well as attenuation and reflection of splices and terminations. In some systems, perform maintenance tests every few months and compare historical test results to provide early warning signs of degradation. In very high capacity or critical systems, employ automated testing devices to test the integrity of the system every few minutes to give immediate warning of degradation or outages.

2.2.3.3 Troubleshooting

During cable restoration, perform testing first to identify the cause of the outage (transmitter, receiver, cable, or connector) and to locate the fault in the cable if the outage was caused by the cable. Then perform testing to assess the quality of the repaired system (permanent splices). This subsequent testing is similar to the testing performed at the conclusion of cable installation.

2.3 Optical Tester Families

One of the main families of optical testers is optical handhelds, which consists of handheld devices that allow for the measurement of system power level, insertion loss (IL), ORL, reflectometry, CD, PMD, and AP.

Some handheld testers add the ability to inspect the optical connector, ensuring technicians will not damage the fiber plant when testing.



Examples of JDSU handheld optical testers

2.3.1 Light Sources

A light source is a device that provides a continuous wave (CW) and stable source of energy for attenuation measurements. It includes a source, either a light emitting diode (LED) or laser that is stabilized using an automatic gain control mechanism. LEDs are typically used for multimode fiber. On the other hand, lasers are used for single-mode fiber applications.

The output of light from either an LED or laser source may also have the option of modulation (or chopping) at a given frequency, which the power meter can then be set to detect. This method improves ambient light rejection. In this case, a 2 kHz modulated light source can be used with certain types of detectors to tone the fiber for fiber identification or for confirmation of continuity.

Comparing LEDs and lasers

Characteristics	LEDs	Lasers
Output power	Linearly proportional to the drive current	Proportional to the current above the threshold
Current	Drive current: 50 to 100 mA (peak)	Threshold current: 5 to 40 mA
Coupled power	Moderate	High
Speed	Slower	Faster
Output pattern	Higher	Lower
Bandwidth	Moderate	High
Available wavelengths	0.66 to 1.65 μm	0.78 to 1.65 μm
Spectral width	Wider (40 to 190 nm FWHM)	Narrower (0.00001 to 10 nm FWHM)
Fiber type	Multimode only	Single-mode and multimode
Ease-of-use	Easier	Harder
Lifetime	Longer	Long
Cost	Low	High

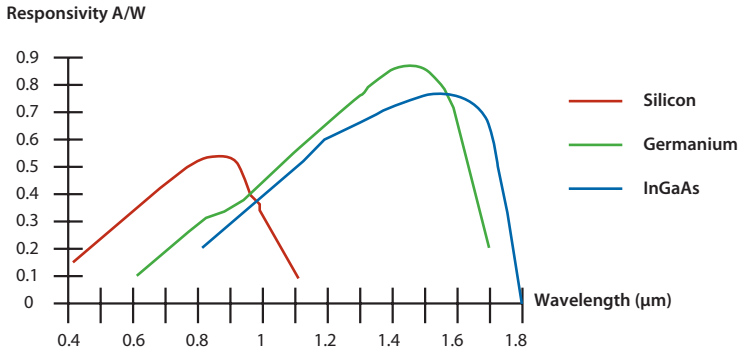
2.3.2 Power Meters

The power meter is the standard tester in a typical fiber optic technician's tool kit. It is an invaluable tool during installation and restoration.

The power meter's main function is to display the incident power on the photodiode. Transmitted and received optical power is only measured with an optical power meter. For transmitted power, the power meter is connected directly to the optical transmitter's output. For received power, the optical transmitter is connected to the fiber system. Then, the power level is read using the power meter at the point on the fiber cable where the optical receiver would be.

2.3.2.1 Detector Specifications

Currently, power meter photodiodes use Silicon (for multimode applications), Germanium (for single-mode and multimode applications), and Indium Gallium Arsenide (InGaAs) (for single-mode and multimode applications) technologies. As shown in the following figure, InGaAs photodiodes are more adapted to the 1625 nm wavelength than Germanium (Ge) photodiodes, because Ge photodiodes are quite sensitive and drop off rapidly at the 1600 nm window.



Responsivity of the three typical detector types

Features found on more sophisticated power meters may include temperature stabilization, the ability to calibrate to different wavelengths, the ability to display the power relative to “reference” input, the ability to introduce attenuation, and a high power option.

2.3.2.2 Dynamic Range

The requirements for a power meter vary depending on the application. Power meters must have enough power to measure the output of the transmitter (to verify operation). They must also be sensitive enough, though, to measure the received power at the far (receive) end of the link. Long-haul telephony systems and cable TV systems use transmitters with outputs as high as +16 dBm and amplifiers with outputs as high as +30 dBm. Receiver power levels can be as low as -36 dBm in systems that use an optical pre-amplifier. In local area networks (LANs), though, both receiver and transmitter power levels are much lower.

The difference between the maximum input and the minimum sensitivity of the power meter is termed the dynamic range. While the dynamic range for a given meter has limits, the useful power range can be extended beyond the dynamic range by placing an attenuator in front of the power meter input. However, this limits the low-end sensitivity of the power meter.

For high power mode, use an internal or external attenuator. If using an internal attenuator, it can be either fixed or switched.

Typical dynamic range requirements for power meters are as follows:

- +20 to -70 dBm for standard power applications
- +26 to -55 dBm for high power applications such as Analog RF transmission in cable TV (CATV) or video overlay in passive optical network (PON) systems.
- -20 to -60 dBm for LAN applications

2.3.2.3 Insertion Loss and Cut Back Measurements

The most accurate way to measure overall attenuation in a fiber is to inject a known level of light in one end and measure the level of light that exits at the other end. Light sources and power meters are the main instruments recommended by ITU-T G650.1 and International Electrotechnical Commission (IEC) 61350 to measure insertion loss. This measurement requires access to both ends of the fiber.

Cut Back Method

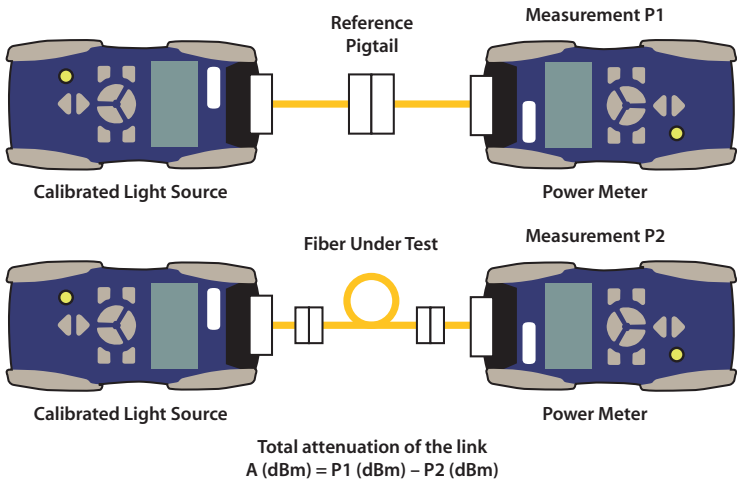
The cut back method is the most accurate measurement, but it is also destructive and cannot be applied in the field. For this reason, it is not used during installation and maintenance. Testing using the cut back method requires first measuring the attenuation of the length of fiber under test. Then, a part of the length of the fiber is cut back from the source, and the attenuation is measured as a reference. Subtracting the two values provides the attenuation of the cut fiber.

Insertion Loss Method

The insertion loss method is a non-destructive method and can be used to measure the attenuation across a fiber, a passive component, or an optical link. With this substitution method, measure the output from a source fiber and a reference fiber directly. Then, obtain a measurement with the fiber under test added to the system. The difference between the two results provides the attenuation of the fiber.

The purpose of the first or reference measurement is to cancel out, as much as possible, the losses caused by the various patch cables.

Contamination of the optical connector end face can cause significant change in optical power. It is important to inspect the end face of both connectors to verify they are clean and undamaged before mating.



The insertion loss method uses two steps to measure the attenuation along a fiber link

It is important to note that significant variations can occur in attenuation measurements if precautions are not taken with the injection conditions.

2.3.3 Loss Test Sets

A loss test set (LTS) combines a power meter and a light source in the same instrument. It is a highly accurate tool and is used to determine the total amount of loss or attenuation of a fiber link.

Tests are usually performed in both directions since results can differ slightly from one direction to the other. For example, attenuation through couplers and fiber core mismatches can significantly differ in either direction. To ensure a better level of accuracy, averages are calculated when qualifying a link.

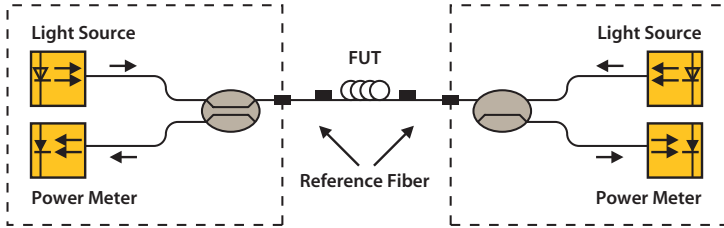
With traditional light sources and power meters, the instruments must either be transferred from one end of the link to the other or a light source and a power meter are required at both ends of the link. The former requires a total of four instruments in order to perform measurements in both directions. With an LTS at each end of the link, tests can be performed in both directions using only two instruments and without the need to transfer them from one end to the other.

Bidirectional Loss Test Sets

With a bidirectional LTS, the light source and power meter are connected to the same output port. An additional external power meter enables using these test sets as stand-alone instruments. Bidirectional LTSs usually offer two ways of referencing the test jumpers for all available wavelengths:

- The side-by-side referencing method connects the two LTSs together using the two test jumpers (see figure that follows).
- The loopback referencing method connects one test jumper from the light source to the external power meter of the same instrument.

Although the side-by-side referencing method increases accuracy, the loopback method allows referencing both instruments independently when not collocated. Connecting both LTSs to the fiber link eliminates further manipulation to carry out the bidirectional measurement.



Insertion loss measurement with two bidirectional LTSs

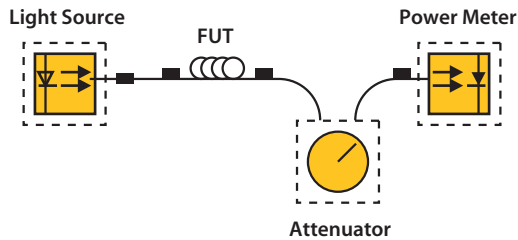
Most of the current LTS instruments are now fully automated bidirectional test instruments. The press of a button performs bidirectional measurements in a few seconds, and immediately saves test results. Automated IL measurement is fast and accurate and requires less training. Meanwhile, incorrect referencing and fiber mishandling remain the major root causes of errors.



T-BERD®/MTS-6000

2.3.4 Attenuators

A fiber optic attenuator is a passive optical component that is intended to reduce the propagation of optical power in the fiber. It can provide either fixed or variable attenuation. An attenuator is ideal for simulating cable loss for the testing of link power margin. A variable attenuator can be set to any loss value within the operating range using a light source and a power meter.



The use of an optical attenuator in optical testing

2.3.5 Optical Loss Budget

Installing a fiber network requires consideration of network topology and equipment specifications. One of the major parameters requiring measurement is optical loss budget, or end-to-end optical link loss. Calculating the optical loss budget of a fiber link requires consideration of the source, detector, and optical transmission line. The transmission link includes source-to-fiber coupling loss, fiber attenuation loss, and loss from all of the components along the line, such as connectors, splices, and passive components.

The optical loss budget sits between maximum and minimum values.

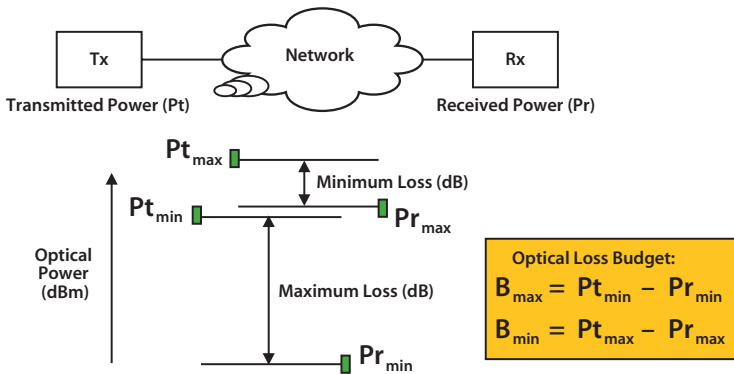
- The maximum value refers to the ratio of the minimum optical power launched by the transmitter to the minimum power level that the receiver can receive while maintaining communication.
- The minimum value refers to the ratio of the maximum optical power launched by the transmitter to the maximum power level that the receiver can receive while maintaining communication.

An example of a typical multimode system includes the following specifications:

- Transmitter output optical power $-12 \text{ dBm} \pm 2 \text{ dBm}$
- Optical receiver sensitivity $\leq -27 \text{ dBm}$
- Optical receiver dynamic range $\geq 18 \text{ dB}$

The transmitter output optical power specification provides the maximum (-10 dBm) and minimum (-14 dBm) power levels that may occur. The optical receiver sensitivity provides the minimum power level that will be detected. The optical receiver dynamic range provides the maximum power level that can be detected ($-27 \text{ dBm} + 18 \text{ dBm} = -9 \text{ dBm}$).

In this example, the maximum optical loss budget is 13 dB based on a minimum output optical power of the transmitter of -14 dBm and a minimum optical receiver sensitivity of -27 dBm .



Calculating the optical loss budget

Optical loss budgets must consider the power margins of the cable and equipment, which cover allowances for the effects of time and environmental factors (launched power, receiver sensitivity, connector, or splice degradation). Calculating the optical loss budget uses typical values of attenuations of the different fiber components.

- 0.2 dB/km for single-mode fiber loss at 1550 nm
- 0.35 dB/km for single-mode fiber loss at 1310 nm
- 1 dB/km for multimode fiber loss at 1300 nm
- 3 dB/km for multimode fiber loss at 850 nm
- 0.05 dB for a fusion splice
- 0.3 dB for a mechanical splice
- 0.5 dB for a connector pair
- 3.5 dB for a 1 to 2 splitter (3 dB splitting loss plus 0.5 dB excess loss)

After completing the calculation of the overall optical loss budget, the cable can be installed.

Example of a typical optical loss budget calculation

Network	Short Haul	Medium Haul	Long Haul
Distance (km)	30	80	200
Fiber loss (dB/km) at 1550 nm	0.25	0.22	0.19
Total fiber loss (dB/km)	7.5	17.6	38
Number of splices	15	40	50
Average splice loss	0.1	0.1	0.05
Total splice loss	1.5	4	2.5
Number of connectors	2	2	2
Average connector loss	0.5	0.5	0.5
Total connector loss	1	1	1
TOTAL LOSS	10	22.6	41.5

2.3.6 Optical Return Loss Meters

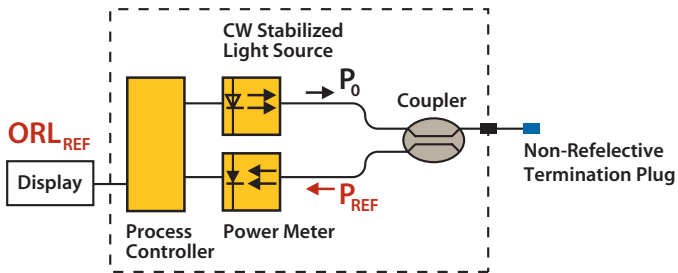
Several methods can be used to measure ORL. The most common methods use either an optical continuous wave reflectometer (OCWR) or an optical time domain reflectometer (OTDR).

2.3.6.1 OCWR Method

Using an OCWR, the light source launches a single wavelength of light at a known power level (P_0) into the fiber optic system to the fiber under test. The wavelength must be similar to the wavelength that the communication system will use in its intended application. A directional coupler then routes the backreflections to the detector in the optical power meter.

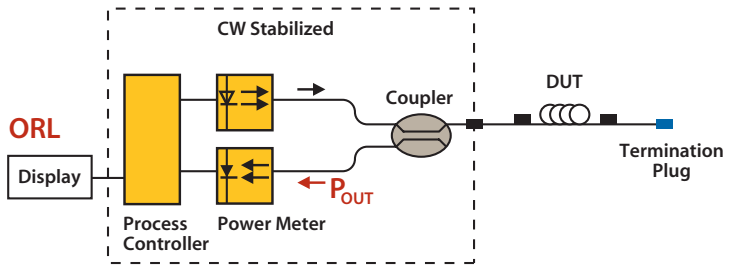
Perform these two steps when measuring the ORL with an OCWR:

1. Take a reference optical power measurement (background return loss) using a non-reflective (< -70 dB) termination plug, which can be replaced by a mandrel wrap, using an index-matching gel or a non-reflective terminator.



ORL referencing using the OCWR method

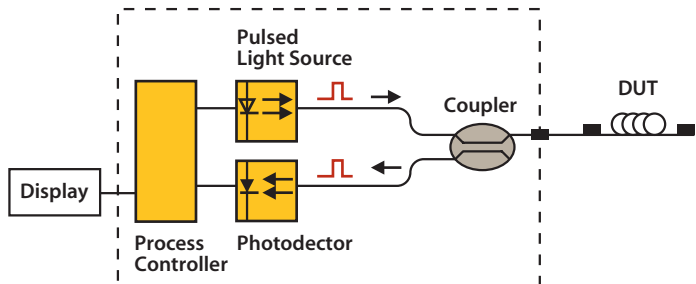
- Once referencing is complete, connect the jumper (coupler/splitter) to the device under test (DUT). Take care at the DUT termination to avoid glass-to-air backreflection (-14 dB), which will affect the ORL value. Then calculate the ORL after measuring the level of reflected optical power in the DUT.



ORL measurement using the OCWR method

2.3.6.2 OTDR Method

The OTDR launches light pulses into the fiber under test and collects backscatter information as well as Fresnel reflections. The light received by the OTDR corresponds to the reflected power according to the injected pulse width.



Setup using the OTDR method

Calculate the ORL after measuring the level of reflected optical power in the fiber under test according to the pulse width.

$$ORL = 10 \text{ Log} \left(\frac{P_0 \Delta t}{\int P_r(z) \cdot dz} \right)$$

Where P_0 is the output power of the OTDR, Δt is the OTDR pulse width, and $\int P_r(z) \cdot dz$ is the total backreflection over the distance of the fiber.

2.3.6.3 Differences in the OCWR and OTDR Methods

It is easier to perform the ORL measurement with an OTDR than with an OCWR because it does not require power output referencing. For technicians familiar with OTDR measurements, the ORL value becomes a de facto standard. The JDSU optical test platforms offer additional value with an automatic ORL measurement while measuring OTDR trace. Using an OTDR also enables measuring the ORL for a given fiber span or for a specific point on the fiber, such as connector reflectance.

However, the OCWR method remains more accurate (approximately ± 0.5 dB) than the OTDR method (approximately ± 2 dB) and allows for the measurement of very short fiber lengths, such as 1 or 2 m patch cords.

Comparing OCWR and OTDR

Characteristics	OCWR	OTDR
Spatial resolution	No	Yes
Accuracy (typical)	± 0.5 dB	± 2 dB
Dynamic range	Up to 70 dB	—
Typical applications	<ul style="list-style-type: none"> Total link ORL and isolated event reflectance measurements during fiber installation and commissioning 	<ul style="list-style-type: none"> Spatial characterization of reflective events and estimation of the total ORL during installation Perfect tool for troubleshooting when discrete elements contributing to the ORL must be identified
Strengths	<ul style="list-style-type: none"> Accurate Fast Provides real-time results Simple and easy (direct result) 	<ul style="list-style-type: none"> Locates reflective events Single-ended measurement
Weaknesses	<ul style="list-style-type: none"> Manipulations (reference measurements required) 	<ul style="list-style-type: none"> Accuracy Long acquisition times

2.3.7 Mini-OTDR and Fault Locators

Using the same basic technology as the OTDR, a new class of instruments became available in the early 1990s. Known as mini-OTDRs, these fiber test instruments are typically battery-powered, lightweight, and small enough to carry in one hand.

The simplest and earliest designs of the mini-OTDRs provided fault location at a minimum, and some provided rudimentary analysis (attenuation, rate of attenuation, distance, and reflectance) of fiber systems. Modern designs mimic the capabilities of mainframe OTDRs, including sophisticated analysis (automatic event detection, table of events, optical return loss, trace overlay, and bidirectional analysis) of fiber links, data storage capabilities, additional functionality (light source, power meter, talk set, and visual fault locator), and even the modularity formerly found only in mainframe OTDRs.

The mini-OTDR has become the popular choice for pre-installation and restoration testing where ease-of-use and mobility are important.



JDSU mini-OTDR test instrument

2.3.8 Fiber Characterization Testing

The growing demand for 10 GigE and 10 Gbps synchronous optical network/synchronous digital hierarchy (SONET/SDH) systems, as well as the emergence of 40G/100G, requires that more and more fiber links be fully characterized. 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, add to the complexity of testing these networks.

Optical link and network characterization is not simply one test function. Rather, it is a comprehensive collection of point-to-point physical layer optical tests that measure and determine the quality and potential transmission capability of a given optical fiber.

Link Characterization

Link characterization measures the fiber performance and the quality of interconnections, such as splice or connectors.

The suite of tests used depends mostly on the user's methods and procedure. These tests could be unidirectional or bidirectional and comprise some or all of the following measurements covering the required test parameters.

Network Characterization

Network characterization provides the network baseline measurements before turning up the transmission system. Measurements are performed through the optical amplifiers, dispersion compensators, and the elements in the line. It is a limited suite of tests compared to link characterization.

Perform link and network characterization measurements during fiber installation, final commissioning, upgrades, and maintenance. If one or more of these parameters do not meet with defined thresholds (provided by international standards or operators/equipment manufacturers), the network will not work properly nor upgraded to high bit rate transmission.

Test Parameters	Measurement Tools
Connector Inspection	Video inspection scope
Insertion Loss measurement	OFl module
Distance measurement (fiber length)	OTDR module
Connectors/splice measurements	OTDR module
Reflectance measurements	OTDR module
ORL measurements	OFl module
PMD measurements	PMD analyzer
CD measurement	CD analyzer
AP measurements	Spectral analyzer

Test Parameters	Measurement Tools
Connector Inspection	Video inspection scope
PMD measurements	PMD analyzer
CD measurement	CD analyzer
AP measurements	Spectral analyzer

Main dispersion thresholds according to the transmission rate (NRZ coding format)

Bit Rate per Channel	SONET/SDH	PMD Delay Limit	Maximum CD @ 1550 nm
2.5 Gbps	OC-48/STM-16	40 ps	18000 ps
10 Gbps	OC-192/STM-64	10 ps	1176 ps
40 Gbps	OC-768/STM-256	2.5 ps	74 ps
10 Gige	—	5 ps	735 ps

Most fiber characterization test platforms are modular in design and contain a mainframe with various test modules, a connector inspection scope, and cleaning materials. These platforms can usually perform complete link and/or network characterization.



JDSU fiber characterization test platform with USB inspection scope

Fiber characterization test platforms contain a controller, display, operator controls, and optional equipment, such as a talk set, input/output interfaces, and hard disk drive. Test modules plug into or stack onto the controller to achieve the required testing capabilities. Test modules have single or multiple measurement capabilities, depending on the measurement method. For example, CD/PMD/AP testing capabilities may be offered in one test module, IL and

ORL in the second, and multi-wavelength OTDR in a third, allowing for complete fiber characterization using one small, lightweight unit. Plug in the connector inspection scope to the controller unit in order to inspect the connector end face before connecting the fiber to the test platform.

Contamination of the optical connector end face can cause significant changes in attenuation and reflectance. It is important to inspect the end face of both connectors to verify they are clean and undamaged before mating.

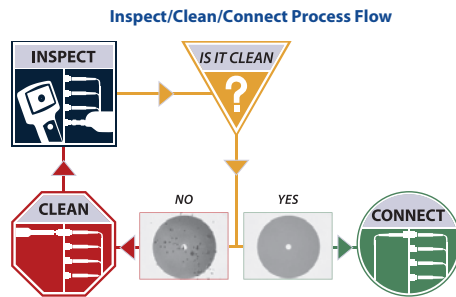
2.3.9 Video Inspection Scopes

Video inspection scopes are portable video microscopes used to inspect fiber optic terminations. They are essential tools for anyone handling, connecting, or testing optical components or systems. Made with an LED light source and a video camera (CCD), video inspection scopes are used to inspect connectors on optical cables, or installed connectors located inside hardware devices or on the backside of patch panels. The use of a video inspection scope eliminates the need to access the backside of patch panels or to disassemble hardware devices prior to inspection.



A video inspection scope with a handheld display

Visually inspecting fiber interconnects provides the only way to determine if connectors are clean prior to mating them. A video microscope magnifies an image of a connector end face for viewing on either a laptop or portable display, depending on the product used.



Optical Connector Inspect/Clean/Connect Process

Probe microscopes can inspect both sides of the optical connection.



Patch cord inspection



Bulkhead inspection

Patch cords are easy to access and view compared to the fiber inside the bulkhead, which is frequently overlooked. The bulkhead side may only be half of the connection, but it is far more likely to be dirty and problematic.

*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.*

IEC Standard 61300-3-35

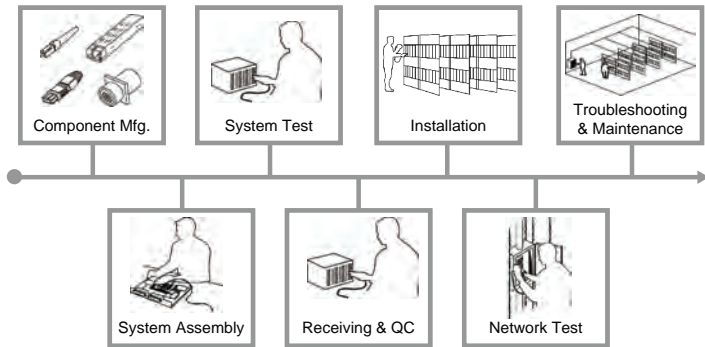
Inspecting to the IEC Standard 61300-3-35 is a global common set of requirements for fiber optic connector end face quality designed to guarantee insertion loss and return loss performance. The Standard contains pass/fail requirements for inspection and analysis of the end face of an optical connector, specifying separate criteria for different types of connections (for example, SM-PC, SM-UPC, SM-APC, MM, and multi-fiber connectors). For more detail on the Standard, copies of the copyrighted document are available for purchase at www.ansi.org by searching for “61300-3-35”.

These criteria are designed to guarantee a common level of performance in an increasingly difficult environment where fiber is penetrating deeper into the network and being handled by more technicians, many of whom may be unfamiliar with the criticality of fiber optical connector end face quality or possess the experience and technical knowledge required to properly assess it.

The standard is designed to be used as a common quality reference between supplier and customer, and between work groups in several ways:

- As a requirement from the customer to the supplier (for example, integrator to component supplier or operator to contractor)
- As a guarantee of product quality and performance from the supplier to the customer (for example, manufacturer to customer, contractor to network owner, or between work groups within an organization)
- As a guarantee of network quality and performance within an organization

As more stages in the fiber optic product life cycle are outsourced to disparate vendors, the standard takes on renewed importance in ensuring the optimized performance of today's fiber-dense networks.



Stages where fiber should be inspected

A video probe microscope system consists of the probe microscope, an adapter or tip to attach to the fiber under test, and a display to show the image of the fiber end face.



Video probe microscope system

Many probe microscopes are capable of using a PC, laptop, or other test instrument for their display, enabling storage of fiber images.



Probe scope attached to a laptop



Probe scope attached to an OTDR

The JDSU P5000 digital inspection microscope adds analysis capability to the fiber end face with Pass/Fail results based on user-defined or industry standard criteria.



Pass/Fail image analysis on laptop



Pass/Fail image analysis on OTDR

2.3.10 Other Test Tools

It becomes more and more common to have test platforms with all test functions integrated. Meanwhile, stand-alone test tools are widely deployed and used by field technicians as they provide flexibility and dedicated solutions for the day-to-day work.

2.3.10.1 Talk Sets

Talk sets transmit voice over installed fiber cable, allowing for communication between technicians who are splicing or testing the fiber, even in the field. Talk sets are available for both single-mode and multimode applications. Talk sets can replace mobile or land-based telecommunication methods, which may not be cost-effective or may not operate in the field.

2.3.10.2 Visual Fault Locators

Visual fault locators (VFLs) are red light lasers that can visually locate faults, up to approximately 5 kilometers away. Sending visual light lets technicians easily see breaks and bends in the fiber as the light exits it, making them especially useful for continuity testing of patch cords, jumpers, or short fiber sections.



A visual fault locator

Also use VFLs in conjunction with splicing machines to identify fibers to be joined with an OTDR for analysis of failures that occur within the dead zone.

The most popular VFLs are composed of a HeNe source and can use 635, 650, or 670 nm lasers or LEDs, depending on the required application.

- 670 nm VFLs perform better at longer distances
- 635 nm VFLs provide higher visual accuracy

2.3.10.3 Fiber Identifiers

Fiber identifiers (FIs) are test instruments that can identify an optical fiber through detection of the optical signals transmitted through single-mode fiber. Utilizing local detection technology (non-destructive macro-bend detection) the FI eliminates the need to open the fiber at the splice point for identification. FIs can detect continuous wave, live optical transmission, and most 270 Hz, 1 kHz, and 2 kHz modulated tones. Some FI models use LEDs to simply indicate the presence of traffic on the fiber as well as the direction of the transmission and the modulated tones. Other FI models can measure and display the fiber's relative power.



A fiber identifier

2.3.10.4 Clip-on Devices

Use clip-on devices in conjunction with a suitable light source to measure power without disconnecting or damaging the fiber. Clip-on devices perform measurements by inserting a controlled bend in the fiber and measuring the level of light that exits. This measurement can be performed either non-intrusively (low bend) or intrusively (strong bend).

2.3.11 Monitoring and Remote Test Systems

Integrate this test equipment into an automated monitoring system or connect it to a network operation center (NOC). The system monitors the network continuously, alerting technicians and managers to faults as they occur. As a result, it dramatically reduces network downtime, maintenance resource requirements, and costs, enabling network operators to improve the quality of their services and maintain cost-effective service level agreements (SLAs).

A Remote Fiber Test System (RFTS) consists of a series of remote test units, a central server, and multiple client stations or machines using associated web-based applications.

Remote Test Units

Install remote test units (RTUs) at strategic points throughout the optical network.

Each unit includes an optical switch to connect to individual fibers and one or more optical modules, such as an OTDR, for measuring and processing initial data.

Monitor fibers in real time, 24 hours a day, 7 days a week according to user-programmable schedules.

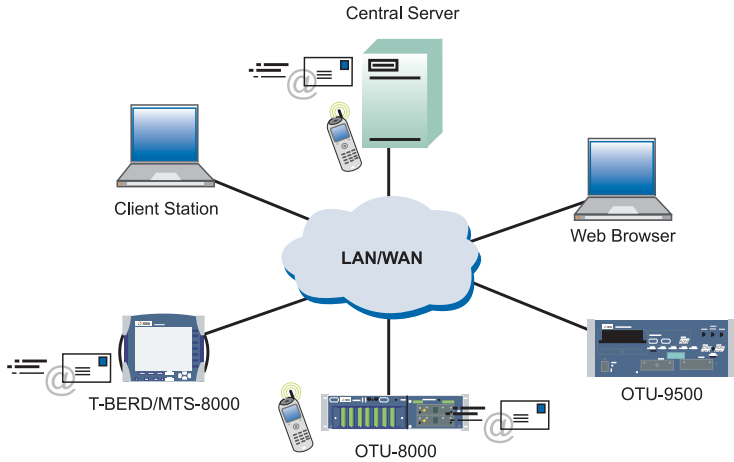
Central Server

At the heart of an RFTS is the central server database that stores and manages all the system information.

Data pulled from RTUs in the field is mapped to the central database and combined with routing records and geographical information, enabling maintenance teams to access precise fault location details.

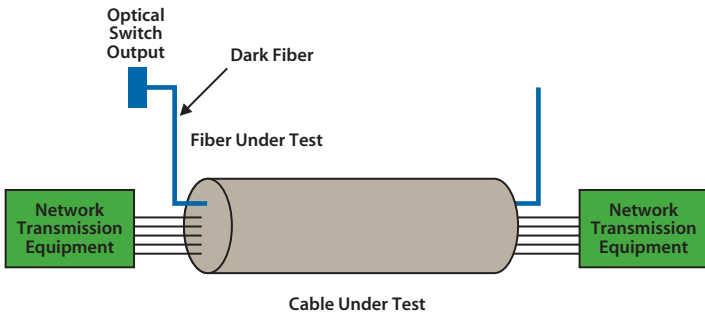
Client Stations

Client stations provide access to all system data for management and engineering center use. They also support the setup and documentation of network structures and provide alarm management and network availability reporting functions.



Example of JDSU RFTS platform (ONMS)

Most network operators initially use a fiber monitoring system to look for and sectionalize a catastrophic link failure. In this case, the RTU is connected to only one or two out-of-service fibers (dark fiber) in a multi-fiber link. In the event of a catastrophic break, this setup assumes that all of the fiber strands will be cut.

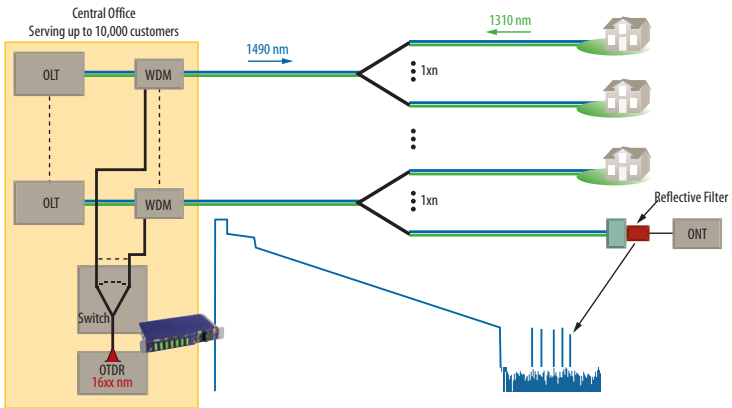


Out-of-service link monitoring

PON Remote Test System

PONs can be automatically monitored in service if PON leg terminations are reflective (see figure about PON monitoring principle). The level of the peak that the reflective termination generates is checked at each acquisition. The peak disappears if the fiber is cut or its reflective termination level decreases because of fiber attenuation. This system enables checking fiber continuity from the central office to the customer. When it detects a fiber cut (a peak is missing), it can accurately locate it using the OTDR.

This system lets engineers at the NOC know whether the problem originates with the fiber or the equipment (optical line termination [OLT], optical network unit [ONU], optical network termination [ONT]), avoiding expensive and unnecessary technician dispatches.

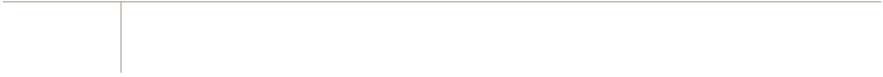


PON monitoring principle



Optical Time Domain Reflectometry

Chapter 3



3.1 Introduction to OTDR

An optical time domain reflectometer (OTDR) is a fiber optic tester for the characterization of fiber and optical networks. The purpose of an OTDR is to detect, locate, and measure events at any location on the fiber link.

One of the main benefits of an OTDR is that it operates as a one-dimensional radar system, allowing for complete fiber characterization from only one end of the fiber. The resolution of an OTDR is between 4 centimeters and 40 meters.

An OTDR generates geographic information regarding localized loss and reflective events, providing technicians with a pictorial and permanent record of the fiber's characteristics, which may be used as the fiber's performance baseline.

3.2 Fiber Phenomena

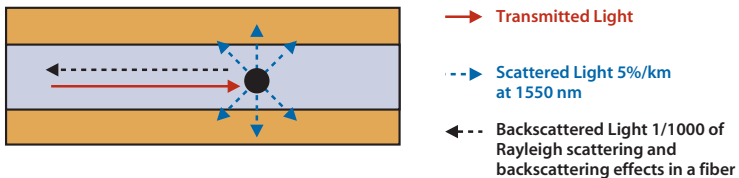
The ability of the OTDR to characterize a fiber is based on detecting small signals that are returned back to it in response to the injection of a large signal, a process similar to radar technology. In this regard, the OTDR depends on two types of optical phenomena: Rayleigh scattering and Fresnel reflections, the differences of which are as follows:

- Rayleigh scattering is intrinsic to the fiber material itself and is present along the entire length of the fiber. Rayleigh scattering is uniform along the length of the fiber; therefore, its discontinuities can be used to identify anomalies in the transmission along the fiber link.
- Fresnel reflections, on the other hand, are point events and occur only where the fiber comes in contact with air or another media, such as a mechanical connection, splice, or joint.

3.2.1 Rayleigh Scattering and Backscattering

When injecting a pulse of light into fiber, some of the photons of light scatter in random directions due to microscopic particles, an effect referred to as Rayleigh scattering. This effect provides amplitude and temporal information along the length of the fiber.

In addition, some of the light is scattered back in the opposite direction of the pulse, which is referred to as the backscattered signal.



Rayleigh scattering and backscattering effects in a fiber

Scattering loss is the main loss mechanism for fiber operating in the three telecom windows (850, 1310, and 1550 nm). Typically, a single-mode fiber transmitting light at 1550 nm with a fiber scattering coefficient (α_s) of 0.20 dB/km will lose 5 percent of the transmitted power over a 1 km section of fiber.

The fiber backscattering factor (S) describes the ratio between the backscattered power and the scattered power. The S factor is typically proportional to the square of the numerical aperture (NA).

Depending on the fiber scattering coefficient (α_s) and the fiber backscattering factor (S), the fiber backscatter coefficient (K) is the ratio of the backscattered power to the energy launched into the fiber. The logarithmic value of the fiber backscatter coefficient, normalized to a 1 ns pulse duration, is given by:

$$K_{ns} \text{ (dB)} = 10 \text{ Log } K_{(S^{-1})} - 90 \text{ dB}$$

When K_{ns} is -80 dB, then for a 1 ns pulse duration, the backscatter power is -80 dB below the incident pulse peak power.

It is important to note that -80 dB at 1 ns is equivalent to -50 dB at 1 μ s.

$$K_{-S} \text{ (dB)} = K_{ns} \text{ (dB)} + 30 \text{ dB}$$

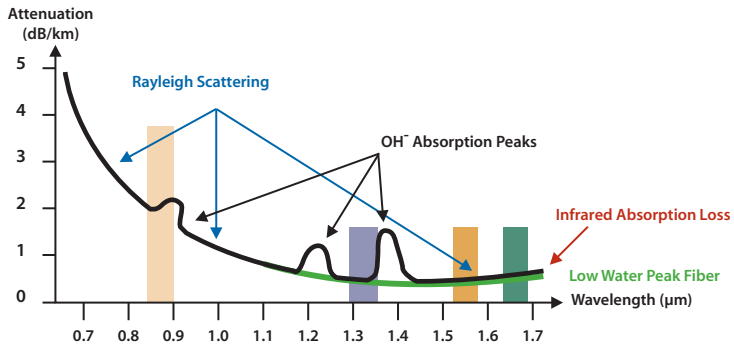
The Rayleigh scattering effect is similar to shining a flashlight in the fog at night. The light beam gets diffused, or scattered, by the particles of moisture. A thick fog will scatter more of the light because there are more water particles to obstruct it.

The backscattering effect depends on the launched power P_0 (W), the pulsewidth Δt (s), the backscattering coefficient $K_{(S^{-1})}$, the distance d (m), and the fiber attenuation a (dB/km).

$$\text{Backscattering} = P_0 \cdot \Delta t \cdot K_{(S^{-1})} \cdot 10^{-axd/5}$$

A higher density of dopants in a fiber will also create more scattering and thus higher levels of attenuation per kilometer. An OTDR can measure the levels of backscattering very accurately and can measure small variations in the characteristics of fiber at any point along its length.

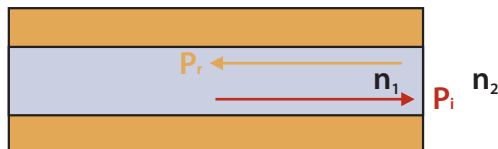
While Rayleigh scattering is quite uniform down the length of any given fiber, the magnitude of Rayleigh scattering varies significantly at different wavelengths (as shown in the following diagram) and with different fiber manufacturers.



Fiber attenuation as a function of wavelength

3.2.2 Fresnel Reflection and Backreflection

Fresnel reflection occurs when light reflects off a boundary of two optical transmissive materials, each having a different refractive index. This boundary can occur at a joint (connector or mechanical splice), at a non-terminated fiber end, or at a break.



Light reflection phenomenon

3.2.2.1 Power Reflection Factor

$$R = \frac{P_r}{P_i} = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}; \text{ from fiber to air } R = 4\%$$

The magnitude of the Fresnel reflection is dependent on the relative difference between the two refractive indexes. The power level of reflected light depends on the boundary surface smoothness.

3.2.2.2 Backreflection

Backreflection, or reflectance, is the amount of light that is reflected back from an optical component of a transmission link (a connector, joint, or mechanical splice). It is the logarithmic ratio of the reflected power (P_r) to the incident power (P_i) at a particular point.

$$\text{Reflectance} = 10 \text{ Log } \frac{P_r}{P_i}; \text{ expressed in dB } (\leq 0)$$

Where P_r is the reflected power (W), P_i is the incident power (W), and n_1 and n_2 are the refractive indexes.

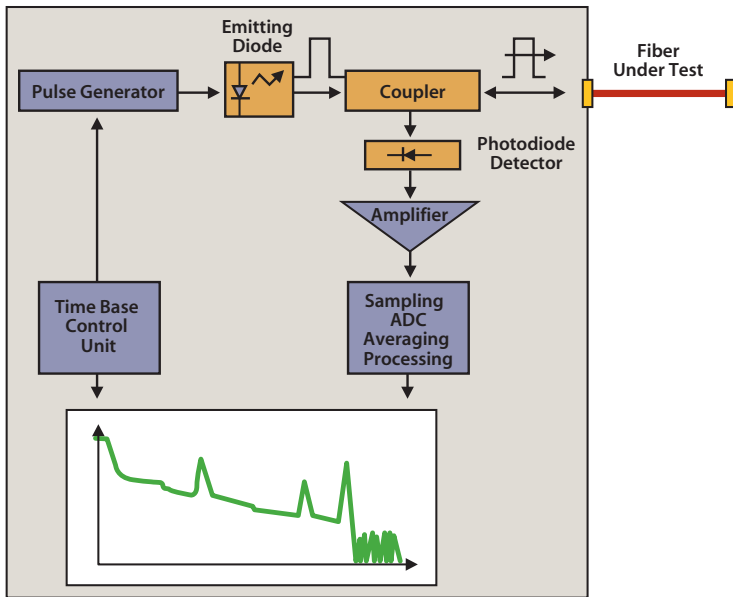
Reflected light from a boundary between a fiber and air has a theoretical value of -14 dB. This value can be over 4000 times more powerful than the level of the backscattered light, meaning that the OTDR detector must be able to process signals that can significantly vary in power. Connectors using an index-matching gel can reduce Fresnel reflection because the gel minimizes the glass-to-air index ratio.

The following table provides the typical reflectance values for a fiber optic connection or break.

Transition Boundaries	Fresnel Reflection
Glass-to-air	-14 dB
PC-to-PC connector	-35 to -50 dB
APC-to-APC connector	-55 to -65 dB

3.3 OTDR Technology

The OTDR injects light energy into the fiber through a laser diode and pulse generator. A coupler fed to the photodiode separates the returning light energy from the injected signal. The optical signal is converted to an electrical value, amplified, sampled, and displayed on a screen.



A schematic diagram showing OTDR technology

3.3.1 Emitting Diodes

Laser diodes are semiconductors in which the light is generated by an electrical current. Emitting diodes are selected according to the central (or peak) wavelength, the wavelength spectral width, and the output power.

Central Wavelength

The central wavelength is the wavelength at which the source emits the most power. It should reflect the test wavelength specifications, for example, 850, 1300, 1310, 1550, and 1625 nm. The central wavelength is usually specified with its uncertainty, which varies from ± 30 to ± 3 nm (for specific temperature-controlled lasers).

Spectral Width

Light is emitted in a range of wavelengths centered around the central wavelength. This range is called the spectral width of the source.

Output Power

For optimal results, as much of the source's power is coupled into the fiber. The key requirement is that the output power of the source must be strong enough to provide sufficient power to the detector at the receiving end.

The two main types of emitting diodes used in OTDR technology are light emitting diodes and laser diodes.

3.3.1.1 Light Emitting Diodes

A light emitting diode (LED) is a semiconductor device that emits a narrow spectrum of light. This effect is a form of electroluminescence. In general, LEDs are less powerful than lasers, but they are much less expensive. LEDs are mainly used in multimode OTDR applications (850 and 1300 nm).

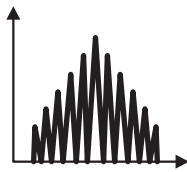
3.3.1.2 Laser Diodes

A laser (light amplification by stimulated emission of radiation) is an optical source that emits photons in a coherent beam. Laser light consists of a single wavelength emitted in a narrow beam.

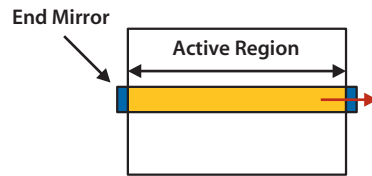
Fabry Perot Laser

The Fabry Perot (FP) laser is the most common type of laser diode used in OTDR design. It is cost-effective and can deliver a high output power level. It is mainly used in single-mode OTDR applications at 1310, 1550, and 1625 nm wavelengths. FP lasers emit light at a number of discrete wavelengths, delivering a spectral width between 5 and 8 nm.

Power (W)



The emitted spectrum of a FP laser

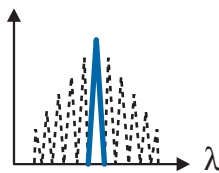


A schematic diagram of a FP laser

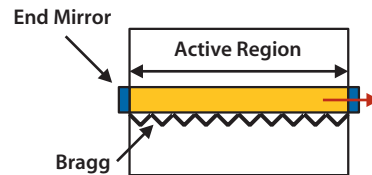
Distributed Feedback Laser

A distributed feedback (DFB) laser is far more precise than a simple FP laser, but its output power delivery capability is much lower. FP lasers emit a lot of harmonics over a wavelength range of 5 and 8 nm. DFB lasers, on the other hand, select only one principal wavelength in the FP laser spectrum, providing a narrow spectral width of < 0.1 nm.

Power (W)



The emitted spectrum of a DFB laser

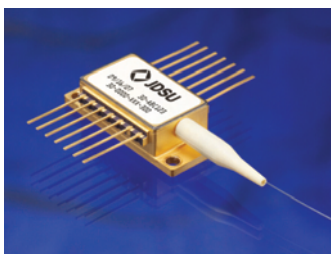


A schematic diagram of a DFB laser

Basically, a DFB laser functions similarly to an FP laser except that it contains a Bragg grating inside its cavity between the two end mirrors.

Comparing LEDs and lasers

Characteristics	LEDs	Lasers
Output power	Linearly proportional to the drive current	Proportional to the current above the threshold
Current	Drive current: 50 to 100 mA (peak)	Threshold current: 5 to 40 mA
Coupled power	Moderate	High
Speed	Slower	Faster
Output pattern	Higher	Lower
Bandwidth	Moderate	High
Available wavelengths	0.66 to 1.65 mm	0.78 to 1.65 mm
Spectral width	Wider (40 to 190 nm FWHM)	Narrower (0.00001 to 10 nm FWHM)
Fiber type	Multimode only	Single-mode and multimode
Ease-of-use	Easier	Harder
Lifetime	Longer	Long
Cost	Low	High



An example of a laser component

3.3.2 Using a Pulse Generator with a Laser Diode

A pulse generator controls a laser diode, which sends powerful light pulses (from 10 mW to 1 W) into the fiber. These pulses can have a width on the order of 2 ns to 20 μ s and a pulse recurrence frequency of several kilohertz. Technicians can set the duration of the pulse (pulse width) for different measurement conditions. The repetition rate of the pulses is limited to the rate at which the pulse return is completed, before launching another pulse. The light goes through the coupler/splitter and into the fiber under test.

The OTDR measures the time difference between the outgoing pulse and the incoming backscattered pulses, hence the term time

domain. The power level of the backscattered signal and the reflected signal is sampled over time. Each measured sample is called an acquisition point, which can be plotted on an amplitude scale with respect to time relative to the timing of the launch pulse. The OTDR then converts this time domain information into distance, based on the user-entered refractive index of the fiber, which is inversely proportional to the velocity of propagation of light in the fiber. The OTDR uses this data to convert time to distance on the OTDR display and divides this value by two to factor in the round-trip (or two-way) travel of light in the fiber. Incorrect or inaccurate user-entered refractive index can result in distances displayed by the OTDR to be inaccurate.

Velocity of propagation, or group delay, of light in a fiber:

$$V = c/n \approx 3 \cdot 10^8 / 1.5 = 2 \cdot 10^8 \text{ m/s}$$

Where V is the group delay, c is the speed of light in a vacuum (2.99792458 m/s), and n is the refractive index.

OTDR time to distance conversion (round trip):

$$L = V \cdot t / 2 = \frac{c \cdot t}{2 \cdot n} = 10^8 \cdot t$$

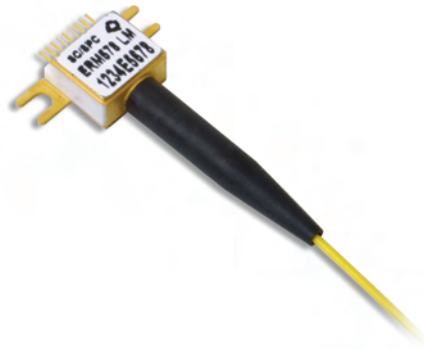
Where L is the distance (m), V is the group delay, t is the pulsewidth (s), c is the speed of light in a vacuum (2.99792458 m/s), and n is the refractive index.

Example: For a 10 ns pulsewidth, $L = 10^8 \times 10 \text{ ns} = 1 \text{ m}$

3.3.3 Photodiodes

OTDR photodiodes are specifically designed to measure the extremely low levels of backscattered light at 0.0001 percent of what the laser diode sends. Photodiodes must be able to detect the relatively high power of reflected pulses of light, which can cause problems when analyzing the results of an OTDR.

The bandwidth, sensitivity, linearity, and dynamic range of the photodiode along with its amplification circuitry are carefully selected and designed for compatibility with the required pulse widths and power levels backscattered from the fiber.

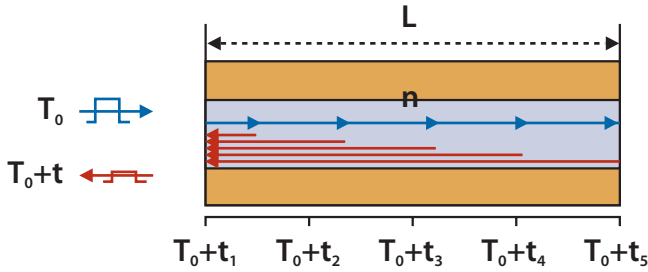


An example of a photodiode component

3.3.4 Time Base and Control Unit

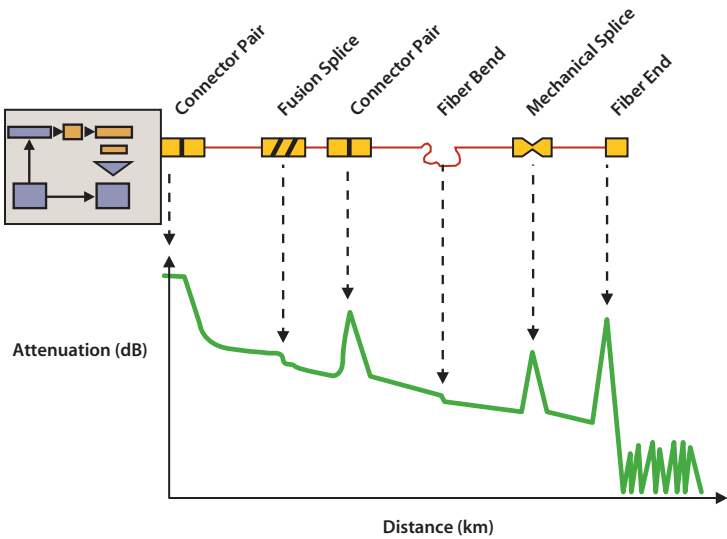
The control unit is the brain of the OTDR. It reads all of the acquisition points, performs the averaging calculations, plots them as a logarithmic function of time, and then displays the resulting trace on the OTDR screen.

The time base controls the pulse width, the spacing between subsequent pulses, and the signal sampling. Multiple passes are used to improve the signal-to-noise ratio (SNR) of the resulting trace. Because noise is random, many data points at a given distance are acquired and averaged, allowing the noise level to average out and approach zero. The resulting data more accurately represents the backscatter or reflection level at a given point. An OTDR may acquire up to 128,000 data points and may fire thousands of pulses. Therefore, it is imperative that the OTDR processor be very powerful, providing technicians with fast performance measurement and analysis.



The OTDR pulse generation principle

The OTDR display shows a vertical scale of attenuation in decibels (dB) and a horizontal scale of distance in kilometers (km) (or feet). Numerous acquisition points are plotted, representing the backscatter signature of the fiber under test.



A typical OTDR trace

3.4 OTDR Specifications

The three key parameters to consider when specifying an OTDR:

- The distance it can see
- How closely it can discriminate events
- How precisely it can locate events

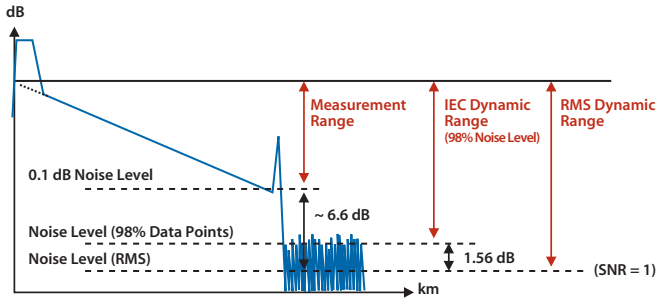
3.4.1 Dynamic Range

The dynamic range is one of the most important characteristics of an OTDR, because it determines the maximum observable length of a fiber; therefore, it also determines the OTDR suitability for analyzing a particular network. The higher the dynamic range, the higher the SNR, and the better the trace and event detection. The dynamic range is relatively difficult to determine because all manufacturers do not use a standard computation method.

3.4.1.1 Definitions of Dynamic Range

Dynamic range can be defined as the difference between the extrapolated point of the backscatter trace at the near end of the fiber (taken at the intersection between the extrapolated trace and the power axis) and the upper level of the noise floor at (or after) the fiber end. Dynamic range is expressed in decibels (dB). The measurement is performed over a 3-minute period, and the results are averaged.

Depending on the noise level reference, there are many definitions of dynamic range. These definitions introduce values that are not immediately comparable.



Different definitions of dynamic range

IEC (98 percent data points of the noise level)

One method of determining dynamic range is to specify the upper noise level as the upper range limit, which contains at least 98 percent of all noise data points. This definition is endorsed by the International Electrotechnical Commission (IEC) in the IEC 61746 standard. Telcordia also recommends this dynamic range value.

RMS

The RMS (root mean square) dynamic range, also termed SNR=1, is the difference between the extrapolated point of the backscatter trace at the near end of the fiber (taken at the intersection between the extrapolated trace and the power axis) and the RMS noise level. If the noise is Gaussian, the RMS value can be compared to the IEC 61746 definition by subtracting 1.56 dB from the RMS dynamic range.

N=0.1 dB

This dynamic range definition provides technicians with an idea of the limit that the OTDR can measure when the noise level is 0.1 dB on the trace. The difference between the N=0.1 and the SNR=1 (RMS) definition is approximately 6.6 dB less, meaning that an OTDR with a dynamic range of 28 dB (SNR=1) can measure a fiber event of 0.1 dB with a dynamic range of 21.4 dB.

End Detection

The end detection dynamic range is the one-way difference between the top of a 4-percent Fresnel reflection at the start of the fiber and the RMS noise level, a value approximately 12 dB higher than the IEC value.

Telcordia Measurement Range

Telcordia defines the measurement range of an OTDR as the maximum attenuation (one way) that can be placed between its optical output port and the accurately identified event to be measured.

1. Splice loss measurement range
2. Fiber attenuation coefficient measurement range
3. Non-reflective fiber end measurement range
4. Reflective fiber end measurement range

4-Percent Fresnel Reflection

This dynamic range measurement is more an echometric parameter than reflectometric. It represents the ability of the instrument to perceive the peak of a Fresnel reflection for which the base cannot be perceived. It is defined as the maximum guaranteed range over which the far end of the fiber is detected. It can have a minimum value of 0.3 dB higher than the highest peak in the noise level.

Whichever noise definition is used, the dynamic range only defines the attenuation loss between two levels on the OTDR trace (from maximum signal level to noise floor level). The closer the signal is to the noise floor, though, the noisier it becomes. The value of the dynamic range for each definition can also be stated according to different measurement conditions.

Typical Value

The typical value represents the average or mean value of the dynamic range for the manufactured OTDRs. An increase of approximately 2 dB is typically shown in comparison with the specified value.

Specified Value

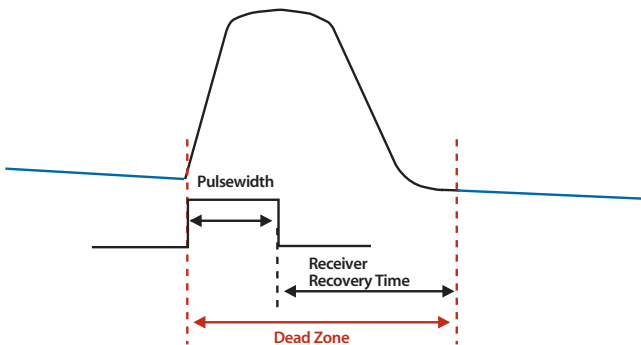
The specified value represents the minimum dynamic range specified by the manufacturer for its OTDR over a temperature range or at room temperature. At low and high temperatures, the dynamic range typically decreases by 1 dB.

3.4.2 Dead Zone

The dead zone of an OTDR is the distance (or time) where the OTDR cannot detect or precisely localize any event or artifact on the fiber link.

3.4.2.1 Why is there a Dead Zone?

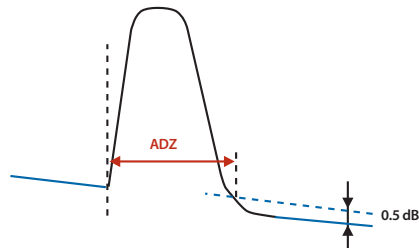
An OTDR is designed to detect the backscattered level all along the fiber link by measuring backscattered signals, which are much smaller than the signal that was injected into the fiber. The photodiode, the component receiving the signal, is designed to receive a given level range. When a strong reflection occurs, the power received by the photodiode can be more than 4,000 times higher than the backscattered power, saturating the photodiode. The photodiode requires time to recover from its saturated condition. During this time, it will not detect the backscattered signal accurately. The length of fiber that is not fully characterized during this period (pulse width + recovery time) is termed the dead zone.



The OTDR dead zone

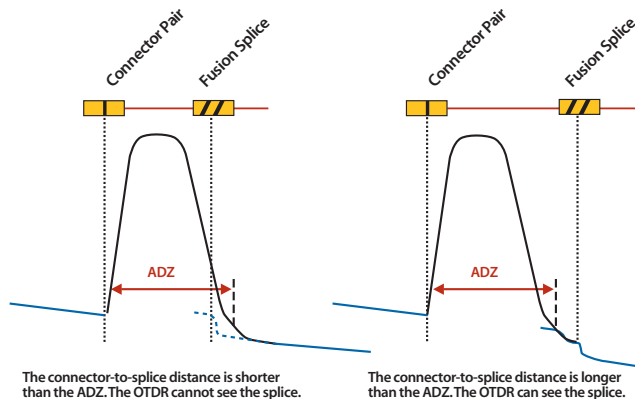
3.4.2.2 Attenuation Dead Zone

The attenuation dead zone (ADZ), as defined in the IEC 61746 standard for a reflective or attenuating event, is the region after the event where the displayed trace deviates from the undisturbed backscatter trace by more than a given vertical value DF (usually 0.5 or 0.1 dB). Telcordia specifies a reflectance of -30 dB and a loss of 0.1 dB and provides several different locations. In general, the higher the reflected power that is sent back to the OTDR, the longer the ADZ.



Measurement of the ADZ

The ADZ depends on the pulse width, the reflectance value of the first reflective event, the loss of this event, and the distance. It usually indicates the minimum distance after a reflective event where a non-reflective event, a splice for example, can be measured.



ADZ and minimum distance measurements

At short pulse widths, the recovery time of the photodiode is the primary determinant of the ADZ and can be five to six times longer than the pulse width itself. At long pulse widths, the pulse width itself is the dominant factor. In this case, the ADZ is, in effect, equal to the pulse width. The ADZ specified for the OTDR is generally measured at the shortest pulse width.

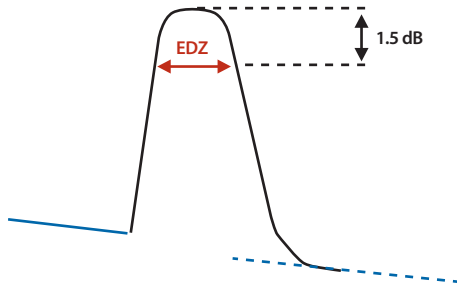
Telcordia specifies two types of ADZs: front-end dead zone and network dead zone. Historically, the connection between the OTDR was highly reflective, which often caused the dead zone at the front end of the OTDR to be much longer than the dead zone that resulted from a reflection in the network. Currently, the OTDR connection has been engineered to have very low reflectance with little difference between the front-end dead zone and the network dead zone.

If the front-end ADZ of the OTDR in use is large, the effect can be minimized using a launch cable.

3.4.2.3 Event Dead Zones

Reflective Events

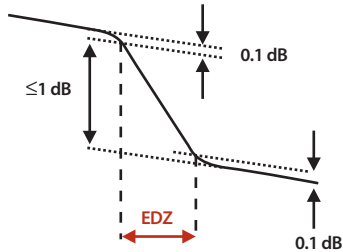
For a reflective event, the event dead zone (EDZ) is defined as the distance between the two opposite points that are 1.5 dB (or full width at half maximum [FWHM]) down from the unsaturated peak of a single reflective event.



The event dead zone (EDZ) of a reflective event

Non-Reflective Events

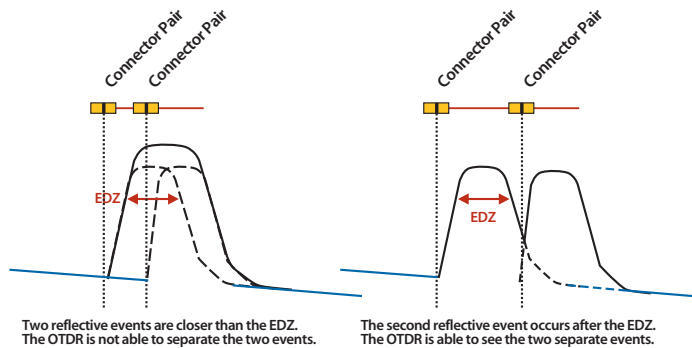
For a non-reflective event, the EDZ refers to the distance between the points where the beginning and ending levels of a splice or a given value (≤ 1 dB) are within ± 0.1 dB of their initial and final values.



The EDZ of a non-reflective event

The EDZ depends on the pulse width and can be reduced using smaller pulse widths. The effects of the front-end EDZ can also be reduced using a launch cable.

The EDZ refers to the minimum distance where two consecutive reflective events can still be distinguished. The distance to each event can be measured, but the separate losses of each event cannot.



EDZ and connector discrimination by the OTDR

3.4.3 Resolution

The four main types of resolution parameters are display (cursor), loss (level), sampling (data point), and distance.

3.4.3.1 Display Resolution

The two types of display resolution are readout and cursor. Readout display resolution refers to the minimum resolution of the displayed value. For example, an attenuation of 0.031 dB will have a resolution of 0.001 dB. The cursor display resolution refers to the minimum distance, or attenuation, between two displayed points. A typical cursor display resolution value is 1 cm or 0.001 dB.

3.4.3.2 Loss Resolution

The resolution of the acquisition circuit governs the loss resolution. For two similar power levels, it specifies the minimum loss difference that can be measured. This value is generally around 0.01 dB.

3.4.3.3 Sampling Resolution

Sampling (or data point) resolution refers to the minimum distance between two acquisition points and can be within centimeters, depending on pulse width and range. In general, the more data points, the better the sampling resolution. Therefore, the number of data points that an OTDR can acquire is an important performance parameter. A typical high-resolution OTDR may have a sampling resolution of 1 cm.

3.4.3.4 Distance Resolution

Distance resolution is very similar to sampling resolution. The ability of the OTDR to locate an event is affected by the sampling resolution. If the OTDR only samples acquisition points every 4 cm, it can only locate a fiber end within ± 4 cm. Similar to the sampling resolution, the distance resolution is a function of the pulse width and range. This specification must not be confused with distance accuracy, which is discussed next.

3.4.4 Accuracy

The accuracy of a measurement refers to its capacity to be compared with a reference value.

3.4.4.1 Linearity (Attenuation Accuracy)

The linearity of the acquisition circuit determines how close an optical level corresponds to an electrical level across the entire range. Most OTDRs have an attenuation accuracy of ± 0.05 dB/dB. Some OTDRs can have a higher attenuation accuracy of ± 0.03 dB/dB. If an OTDR is nonlinear, the section loss values will change significantly for long fiber.

3.4.4.2 Distance Accuracy

The distance accuracy depends on parameters such as group index, time base error, and distance error at the origin.

Group Index

Whereas refractive index refers to a single ray in a fiber, group index refers to the propagation velocity for all of the light pulses in a fiber. The accuracy of the OTDR distance measurements depends on the accuracy of the group index.

Time Base Error

Time base error is due to the inaccuracy of the quartz in the timing mechanism, which can vary from 10^{-4} to 10^{-5} seconds. In order to calculate the distance error, the time base error must be multiplied by the measured distance.

Distance Error at the Origin

A typical distance accuracy value for the JDSU T-BERD®/MTS-8000 OTDR is calculated by:

$$\pm 1 \times 10^{-5} \times \text{distance} \pm 1 \text{ m} \pm \text{sampling resolution} \pm \text{group index uncertainties}$$

3.4.5 Wavelength

OTDRs measure according to wavelength. The main wavelengths for OTDR are 850 and 1300 nm for multimode fiber and 1310, 1550, and 1625 nm for single-mode fiber. A 1625 or 1650 nm laser diode can be used for testing networks with live traffic, commonly referred to as “in-service testing” and used for remote monitoring systems or in fiber-to-the home (FTTH) passive optical network (PON) applications. The purpose of using the 1625 or 1650 nm wavelength is to avoid interference with traffic at 1310 nm and around 1550 nm.

Other wavelengths used for fiber characterization:

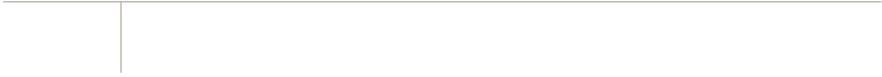
- 1383 nm wavelength used for attenuation measurements around the main fiber absorption peak
- 1420, 1450, and 1480 nm wavelengths used for Raman-amplified systems
- 1490 nm wavelength used for FTTH systems
- 1271 to 1611 nm coarse wavelength division multiplexing (CWDM) wavelengths used for OTDRs dedicated to CWDM system turn-up and troubleshooting

Some OTDRs display the exact laser wavelengths used for measurement. Generally, though, only the generic wavelength is provided.



Using an Optical Time Domain Reflectometer (OTDR)

Chapter 4



4.1 Introductio to OTDR Use

The optical time domain reflectometer OTDR is very versatile with many applications. It is important to select an OTDR with the appropriate specifications for the application necessary. With recent breakthroughs in modularity, some OTDRs, such as the flexible JDSU T-BERD®/MTS family, can be configured to perform testing on nearly any fiber optic network, single-mode or multimode and short or long haul.

The use of an OTDR is broadly defined as a two-step process:

1. Acquisition: The OTDR acquires the data and displays results either numerically or graphically.
2. Measurement: Technicians analyze the data and, based on the results, decide either to store, print, or go to the next fiber acquisition.



4.2 Acquisition

Most modern OTDRs automatically select the optimal acquisition parameters for a particular fiber by sending out test pulses in a process known as auto-configuration. Using the auto-configuration feature, technicians select the wavelength (or wavelengths) to test, the acquisition (or averaging) time, and the fiber parameters (refractive index, for example, if not already entered).

Three major approaches used when configuring an OTDR:

1. Technicians simply allow the OTDR to auto-configure and accept the acquisition parameters the OTDR selects.
2. More experienced technicians allow the OTDR to auto-configure, then analyze the results briefly and change one or more acquisition parameters to optimize the configuration for the particular test requirements.
3. Experienced technicians choose not to use the auto-configuration feature altogether and enter the acquisition parameters based on experience and knowledge of the link under test.

Typically, when testing multi-fiber cables, once the appropriate acquisition parameters are selected, they are locked in. The same parameters are then used for every fiber in the cable. This feature dramatically speeds up the acquisition process and provides for consistency in the data, which is helpful when analyzing or comparing fibers.

The following subsections discuss various acquisition parameters and their effects on the resulting OTDR trace.

4.2.1 Injection Level

The injection level is defined as the power level in which the OTDR injects light into the fiber under test. The higher the injection level, the higher the dynamic range. If the injection level is low, the OTDR trace will contain noise, and measurement accuracy will be diminished.

Poor launch conditions, resulting in low injection levels, are the primary reason for reductions in accuracy.

The presence of dirt on connector faces and damaged or low-quality pigtailed or patch cords serve as the primary causes of low injection levels. It is important that all physical connection points are free of dust and dirt in an optical system. With core diameters of less than 10 μm in single-mode systems, the presence of even a 4 μm speck of dirt or dust (approximately the size of the particulate matter in cigarette smoke) can severely degrade injection levels.

Cleaning kits are available for optical systems from basic tools, such as isopropyl cleaning solution, Joseph paper, compressed air spays, and ready-to-use impregnated wipes, to more advanced methods using cassette cleaners and integrated cleaning systems, such as the JDSU CleanBlast™ system. Mating dirty connectors to the OTDR connector may scratch the OTDR connector, permanently degrading launch conditions.

Some OTDRs, such as the T-BERD/MTS family, display the measured injection level during real-time acquisition or just prior to averaging. The result is displayed on a bar graph using a relative scale, rating the injection level from good to bad.

To determine the relative quality of the injection level, the OTDR looks out a short distance, observes the backscatter returned from the launch pulse, and compares this value to an expected value. It is sometimes possible for the injection level to display as unacceptable when it is in fact acceptable, which can occur if there is an attenuator or splitter on the system near the OTDR. In this case, the backscatter level will be lower than expected as measured by the injection level meter. Although the injection level increases as pulse width increases, the scale displayed is calibrated separately for each pulse width. Therefore, the scale is meaningful at any pulse width, and increasing the pulse width will not change a bad injection level to a good one.

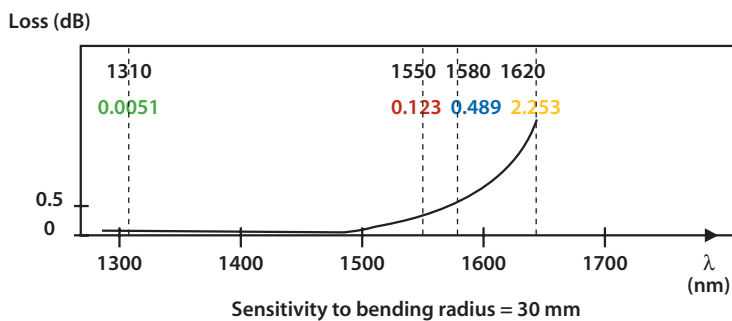
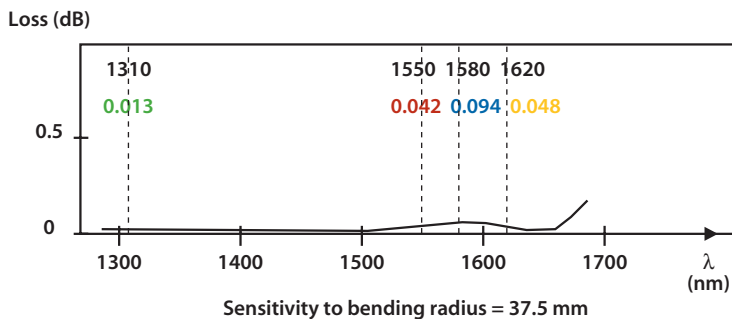
4.2.2 OTDR Wavelength

The behavior of an optical system is directly related to its wavelength of transmission. Optical fiber exhibits different loss characteristics at different wavelengths. In addition, splice loss values also differ at different wavelengths.

In general, test the fiber using the same wavelength used for transmission. Therefore, 850 and/or 1300 nm wavelengths are used for multimode systems, and 1310 and/or 1550 nm wavelengths are used for single-mode systems.

When testing only one wavelength, consider the following parameters:

1. For a given dynamic range, using a wavelength of 1550 nm will see longer distances down the same fiber than a wavelength of 1310 nm due to the lower attenuation in the fiber.
 - 0.35 dB/km at 1310 nm means that approximately 1 dB of signal is lost every 3 km.
 - 0.2 dB/km at 1550 nm means that approximately 1 dB of signal is lost every 5 km.
2. Single-mode fiber has a larger mode field diameter at 1550 than at 1310 nm and at 1625 than at 1550 nm. Larger mode fields are less sensitive to lateral offset during splicing, but they are more sensitive to losses incurred by bending during installation or in the cabling process.
 - 1550 nm is more sensitive to bends in the fiber than 1310 nm, known as macro bending.
 - 1310 nm will generally measure splice and connector losses higher than 1550 nm. These results are from a Corning study of over 250 splices where the 1310 nm values were shown to be typically higher by 0.02 dB over the 1550 nm values for dispersion shifted fiber.



The effects of bending on a fiber

4.2.2.1 Testing from 1310/1550 to 1625 nm

OTDRs serve as ideal tools for detecting and locating bends in a fiber link, as shown in the graph below. The green trace represents measurement at 1310 nm, the violet trace at 1550 nm, and the red trace at 1625 nm.



The OTDR graph shows a bend located at 3040 m at 1550 and 1625 nm

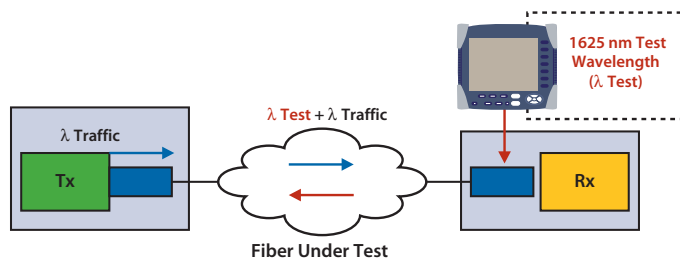
The bending effect is not a new phenomenon. In the past, when the 1550 nm wavelength was first introduced and added to the 1310 nm transmission wavelength, the bending effect was analyzed. For example, many optical fiber reports were generated comparing 1550 nm splice losses to 1310 nm splice losses in order to detect possible bending effects. Now that OTDR technology has moved into the 1625 nm wavelength area of the spectrum, the same analysis of bending effects must occur.

4.2.2.2 When to Test Links at 1625 nm

Networks do not always need to be tested at the 1625 nm wavelength. Three key circumstances require conducting 1625 nm testing.

1. Upgrading of current networks: This is especially important for dense wavelength division multiplexing (DWDM) network upgrades that will use or plan to use the L and U bands.
2. Installation of new fiber networks: With today's testing tools, the added time required to perform testing at 1625 nm compared to current 1310/1550 nm has become negligible. This decrease in testing time has pushed installers to perform testing at all three wavelengths, essentially future-proofing their networks.

3. In-service testing: This is a well-known application used for remote fiber test systems (RFTS) and for all types of networks. However, for maintenance purposes, classical non-L band transmission, or typical PON networks, if couplers are available can be performed at the 1625 nm wavelength without perturbing the 1310/1490/1550 nm transmission. An example of contra-propagation testing is conducting OTDR measurements at the opposite end of the transmission laser. For high-power-level transmission systems, it is mandatory to compensate the test wavelength for the effects of Raman scattering.

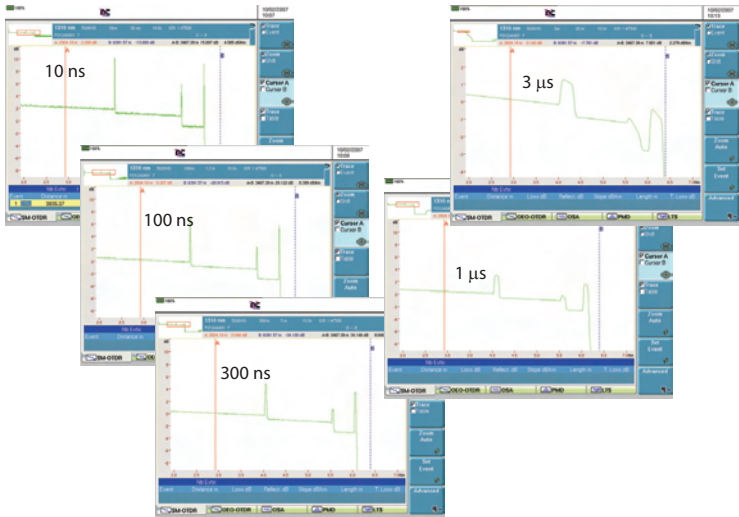


n-service testing at 1625 nm using the contra-propagation method

4.2.3 Pulse Width

The duration of the OTDR pulse width controls the amount of light that is injected into a fiber. The longer the pulse width, the greater the amount of light energy injected. The more light energy injected, the greater the amount of light, which is backscattered or reflected back from the fiber to the OTDR.

Long pulse widths are used to see long distances down a fiber cable. Long pulse widths also produce longer areas in the OTDR trace waveform where measurements are not possible known as the dead zone of the OTDR. Short pulse widths, on the other hand, inject lower levels of light, but they also reduce the OTDR dead zone.



Fiber measurement using different pulse widths

The duration of the pulse width is usually given in nanoseconds, but it can also be estimated in meters according to the following formula:

$$D = \frac{cT}{2n}$$

Where c is the speed of light in a vacuum (2.99792458×10^8 m/s), T is the pulse duration in ns, and n is the refractive index.

For example, a 100 ns pulse can be interpreted as a 10 m pulse.

Comparing pulse width to the fiber length

Time or pulsewidth	5 ns	10 ns	100 ns	1 μ s	10 μ s	20 μ s
Distance or fiber length	0.5 m	1 m	10 m	100 m	1 km	2 km

4.2.4 Range

The range of an OTDR refers to the maximum distance from which the OTDR can acquire data samples. The longer the range, the further the OTDR will shoot pulses down the fiber. The range is generally set at twice the distance to the end of the fiber. If the range is set incorrectly, the trace waveform may contain measurement artifacts, such as ghosts.

4.2.5 Averaging

The OTDR detector functions at extremely low optical power levels (as low as 100 photons per meter of fiber). Averaging is the process by which each acquisition point is sampled repeatedly, and the results are averaged in order to improve the signal-to-noise ratio (SNR).

Selecting the time of acquisition or the number of averages gives technicians control over the process of averaging within the OTDR. The longer the time or the higher the number of averages, the more signal the trace waveform will display in random noise conditions.

The relationship between the acquisition time (number of averages) and the amount of improvement to the SNR is expressed by the following equation:

$$\Delta\text{SNR} = 5 \text{ Log}_{10} \sqrt{N}$$

Where N is the ratio of the two averages.

Note: The noise distribution is considered random for this formula

For example, an acquisition using 3-minute averaging will improve the dynamic range by 1.2 dB when compared to an acquisition using 1-minute averaging.

Averaging improves the SNR by increasing the number of acquisitions, but it also increases the time it takes to average the trace. However, according to the equation, beyond a certain acquisition time, no advantage is gained because only the signal remains. In theory, multiplying the average acquisition time by 4 will provide a +1.5 dB increase in the dynamic range.

4.2.6 Fiber Parameters

Several other parameters related to the fiber can affect OTDR results.

4.2.6.1 Refractive Index

The refractive index (n) is directly related to distance measurements. When comparing distance results from two acquisitions, technicians must ensure that they use the appropriate refractive index. If using the refractive index reported by the fiber manufacturer, the OTDR will report the fiber length accurately.

However, particularly during fault location, technicians want to determine the cable length using an OTDR. Fiber length and cable length are not identical, though, and differ due to the over length of the fiber in the buffer tube and the geometry (helixing) of the buffer tubes in the cable. The ratio between the fiber length and cable length, termed the helix factor, varies depending on the cable fiber count, the cable design, and even the cable manufacturer.

While manufacturers may report the helix factor, the lack of precision of the value causes a large amount of uncertainty in fault location. For this reason, it is often recommended to measure a known length of similarly constructed cable and determine the effective refractive index that will allow the OTDR to report cable length instead of fiber length.

4.2.6.2 Backscatter Coefficient

The backscatter coefficient (K) provides the OTDR with the relative backscatter level of a given fiber. The backscatter coefficient is set at the factory, and generally, technicians will not change this parameter. Changing the backscatter coefficient will affect the reported value of reflectance and the optical return loss.

While the assumption is that the backscatter coefficient for the entire span is consistent, slight variations are possible from one fiber span to another, which can cause measurement anomalies, such as splices with negative loss values (or gainers).

Typical backscatter coefficients at 1 ns for single-mode and multimode fiber are as follows:

- Standard single-mode fiber
 - 79 dB at 1310 nm
 - 81 dB at 1550 nm
 - 82 dB at 1625 nm
- Standard multimode fiber
 - 70 dB at 850 nm
 - 75 dB at 1300 nm

4.3 Measurement

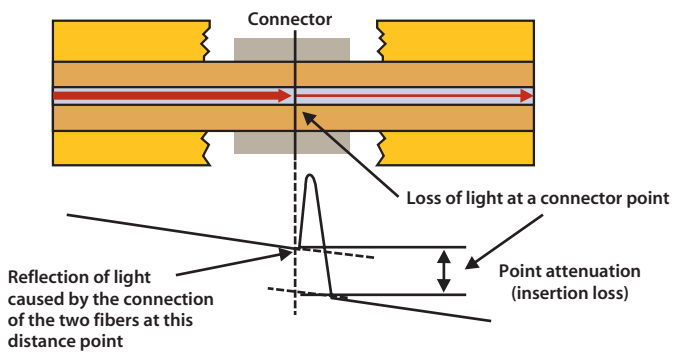
Most modern OTDRs perform fully automatic measurements with very little input from technicians.

4.3.1 Event Interpretation

In general, two types of events occur: reflective and non-reflective.

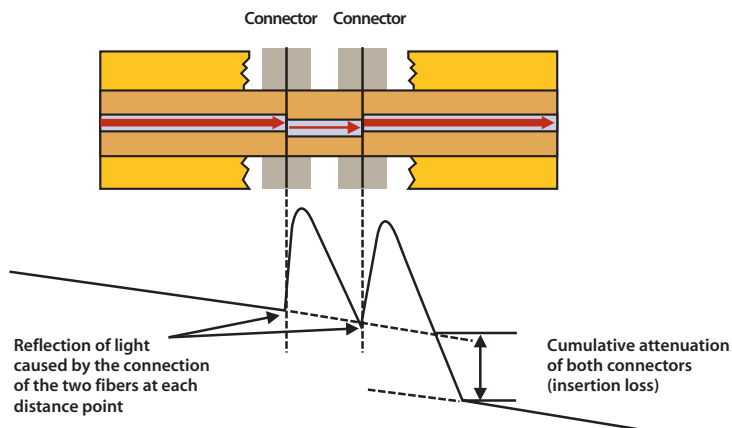
4.3.1.1 Reflective Events

Reflective events occur where discontinuity arises in the fiber, causing an abrupt change in the refractive index. Reflective events can occur at breaks, connector junctions, mechanical splices, or the indeterminate end of fiber. For reflective events, connector loss is typically around 0.5 dB. For mechanical splices, though, the loss typically ranges from 0.1 to 0.2 dB.



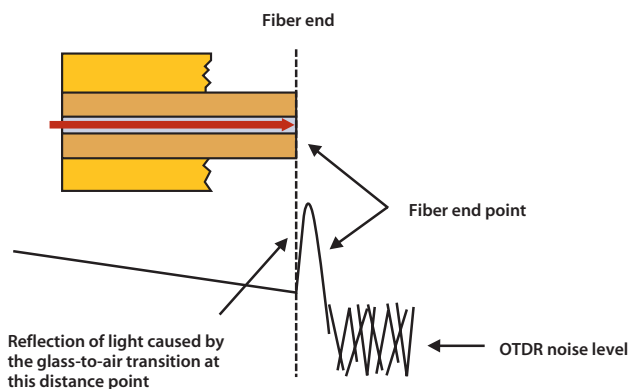
A reflective event at a connector junction

If two reflective events occur very close together, the OTDR may have problems measuring the loss of each event. In this case, it displays the loss of the combined events, which typically occurs when measuring a short fiber length, such as a fiber jumper.



A reflective event at two connector junctions located close together

In the case of a fiber end, the reflective event will fall into the noise and prevent taking the attenuation measurement.

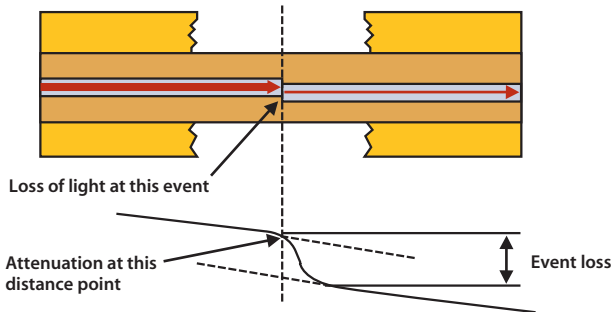


A reflective event at a fiber end

Fiber ends can also cause a non-reflective event. In this case, no reflectance is detected.

4.3.1.2 Non-reflective Events

Non-reflective events occur where discontinuities are absent in the fiber and are generally produced by fusion splices or bending losses, such as macro bends. Typical loss values range from 0.02 to 0.1 dB, depending on the splicing equipment and operator.



A non-reflective event

For non-reflective events, the event loss can appear as an event gain, displaying a step-up on the OTDR trace.

4.3.2 OTDR Measurements

An OTDR can perform the following measurements:

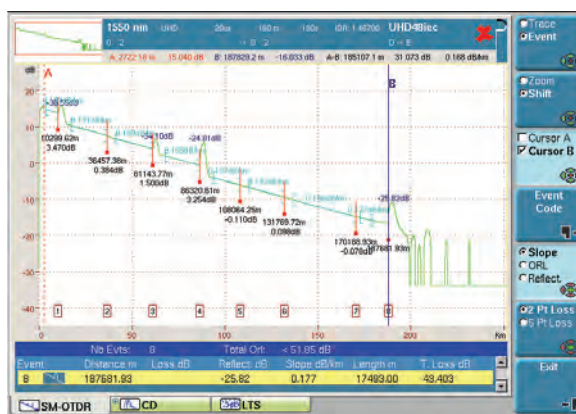
- For each event: Distance location, loss, and reflectance
- For each section of fiber: Section length, section loss (in dB), section loss rate (in dB/km), and optical return loss (ORL) of the section
- For the complete terminated system: Link length, total link loss (in dB), and ORL of the link

4.3.3 Measurement Methods

The OTDR lets technicians perform measurements on the fiber span in several ways: full-automatic, semi-automatic, and manual measurement functions. Technicians can also use a combination of these methods.

4.3.3.1 Full-Automatic Function

Using the full-automatic function, the OTDR detects and measures all of the events, sections, and fiber ends automatically, using an internal detection algorithm.



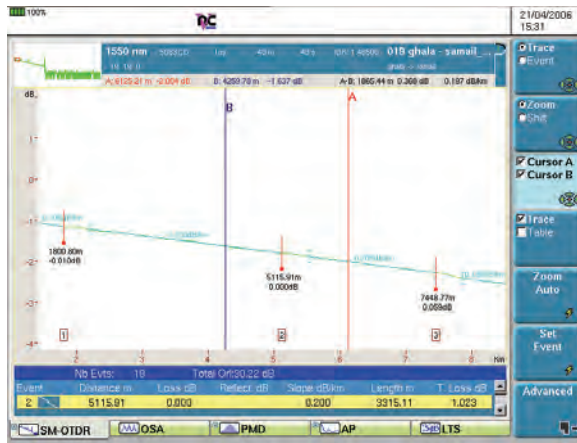
Automatic event detection using the JDSU T-BERD/MTS platforms

4.3.3.2 Semi-Automatic Function

Selecting the semi-automatic function, the OTDR measures and reports an event at each location (distance) with a marker. Markers can be placed either automatically or manually.

The semi-automatic function is of high interest during span acceptance (after splicing), when technicians completely characterize all events along the span in order to establish baseline data. Because automatic detection will not detect and report a non-reflective event with a zero loss, it places a marker at that location so that the semi-automatic analysis will report the zero loss.

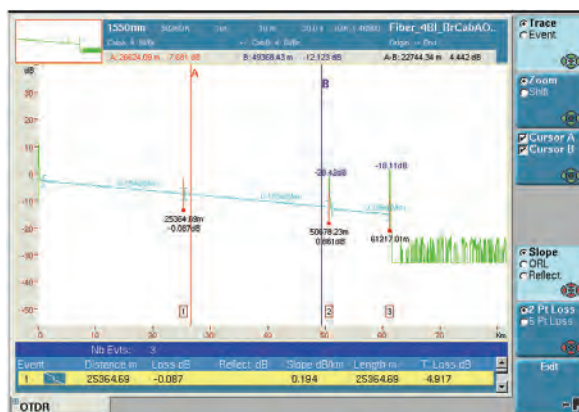
Further analysis of the trace using a PC software application, such as the JDSU OFS-100 FiberTrace, allows for bidirectional analysis of the span. The use of the semi-automatic function at fixed marker locations ensures consistency in the number of events from fiber to fiber and from measurements in the opposite direction.



Semi-automatic measurement of a 0 dB splice loss

4.3.3.3 Manual Measurement Function

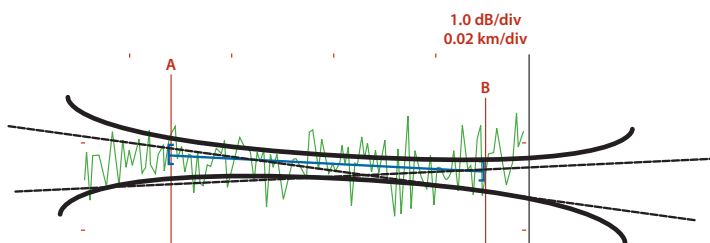
For even more detailed analysis or for special conditions, technicians completely control the measurement function manually. In this case, technicians place two or more cursors on the fiber in order to control the way the OTDR measures the event. Depending on the parameter being measured, technicians may need to position up to five cursors to perform a manual measurement. While this is the slowest and most cumbersome method of measurement, it is important to have this capability available for fiber spans with unusual designs and construction that are difficult to analyze accurately using automated algorithms.



Manual measurement using cursors A and B

4.3.4 Slope

Measure the slope (in dB/km), or fiber linear attenuation, using either the 2-point method or the least squares approximation (LSA) method. The LSA method attempts to determine the measurement line that has the closest fit to the set of acquisition points. The LSA method is the most precise way to measure fiber linear attenuation, but it requires a continuous section of fiber, a minimum number of OTDR acquisition points, and a relatively clean backscatter signal, which is free of noise.



The least squares approximation method

The standard deviation of the slope (dB/km) depends on:

- The local noise level (and distribution)
- The number of acquisition points used by the LSA method

Section loss can be reported in decibels (dB) or decibels per kilometer (dB/km). Typical section losses range from:

- 0.17 to 0.22 dB/km for 1550 nm systems
- 0.30 to 0.35 dB/km for 1310 nm single-mode systems
- 0.5 to 1.5 dB/km for 1300 nm multimode systems
- to 3.5 dB/km for 850 nm systems

4.3.5 Event Loss

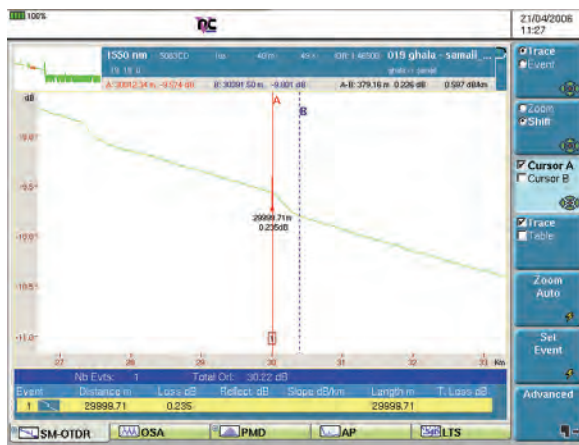
Manual measurement offers two ways to measure event loss: the 2-point method and the 5-point method.

4.3.5.1 The 2-Point Method

For the 2-point method, technicians position the first cursor on the linear backscatter level before the event and the second cursor on the linear backscatter level after the event. The event loss is then the difference between these two cursor measurements.

Use this method for both reflective and non-reflective events. However, the precision of the 2-point method depends on a technician's ability to place the cursors at the correct positions and can be compromised if the trace has a large amount of residual noise. If the trace is very noisy or spiky, then technicians should try to place the cursor on a data point on the trace that is not located at the top of a spike or the bottom of a trough. This is, in effect, a form of visual averaging of the trace.

If technicians are using the 2-point method to measure a point event, such as a splice, as opposed to a length of fiber, then they should be aware that the result will also include the effects of any fiber losses between the cursors because the distance between the cursors is non-zero.



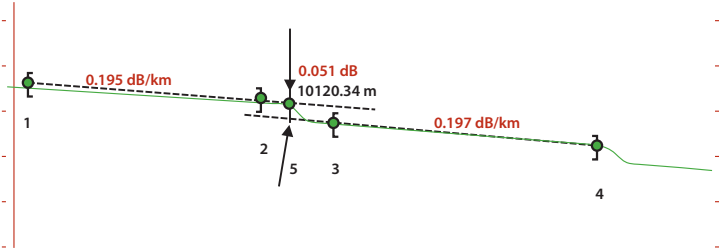
Using the 2-point measurement method between cursors A and B

4.3.5.2 The 5-Point Method

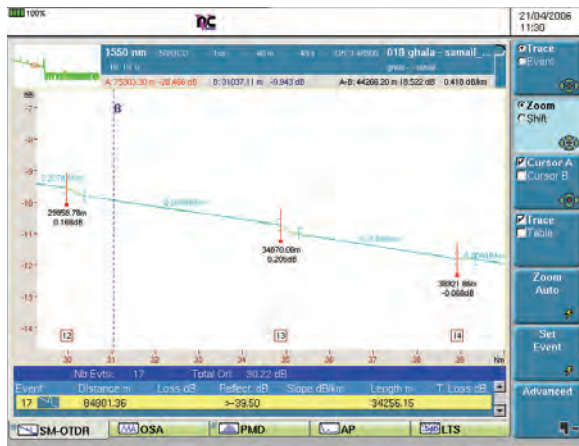
The purpose of the 5-point measurement method for point events is to reduce the effects of noise on the fiber span before and after the event, which is accomplished by performing a least squares approximation analysis on the fiber span. This process minimizes the additional fiber loss that is reported as event loss due to the non-zero distance between the cursors.

For the 5-point method, the software uses the position of the five cursors to extrapolate the fiber data before and after the event and performs a zero distance measurement of the loss at the event location. This method can be used to measure the loss of both non-reflective and reflective events.

Technicians first obtain a slope measurement before and after the event on the linear backscattered level of the trace. The fifth point of measurement is placed just before the event where the backscatter trace suddenly deviates. Technicians then take a loss measurement at this event location. The 5-point method is more precise than the 2-point method because the OTDR compares the difference between two linear backscatter levels.



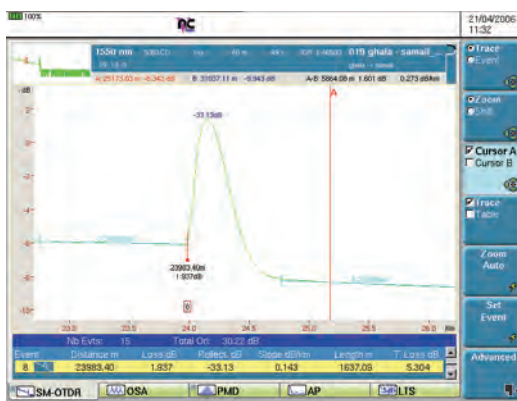
Using the 5-point measurement method



Obtaining a loss measurement

4.3.6 Reflectance

The reflectance of an event represents the ratio of the reflected power to the incident power at a discrete location on the fiber span. Reflectance is expressed in decibels (dB). A small negative value indicates a higher reflection than a large negative value. That is, a reflectance of -33 dB is larger than a reflectance of -60 dB. A larger reflectance will appear as a higher peak on the trace waveform.



Reflectance measurement

The amount of reflection at a connector, break, or mechanical splice depends on the difference in the refractive index between the fiber and the material at the fiber interface (another fiber, air, or index-matching gel) and the geometry of the break or connector (flat, angled, or crushed). Both of these factors allow for capturing a different amount of reflection in the fiber core.

Most mechanical splices use an index-matching gel or fluid to reduce refractive index differences. Smaller differences in the refractive index produce smaller reflections. Some OTDRs can automatically measure the amount of reflecting light by placing one cursor just in front of the reflection, placing another cursor at the top of the reflection, and pressing the appropriate button on the control panel of the OTDR.

4.3.7 Optical Return Loss

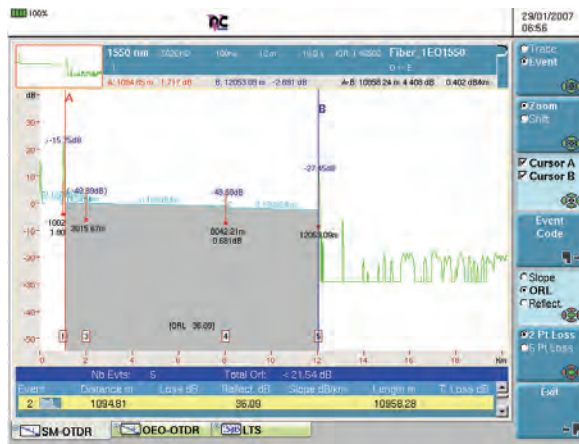
High-performance OTDRs can automatically measure and report a value for the total link ORL. They also provide manual ORL measurement capability to isolate the portion of the link contributing the majority of the ORL.

4.3.7.1 Measuring ORL with an OTDR

The light that the OTDR receives corresponds to the behavior of the reflected power along the fiber link according to the injected pulse width. The integral of this power allows for the calculation of the total back reflection and for the determination of the ORL value.

$$\text{ORL} = 10 \text{ Log} [(P_0 \times \Delta t) / (f P_r(z) dz)]$$

Where P_0 is the output power of the OTDR, Δt is the OTDR pulse width, and $f P_r(z) dz$ is the total backreflected and backscattered power over the distance (partial or total).

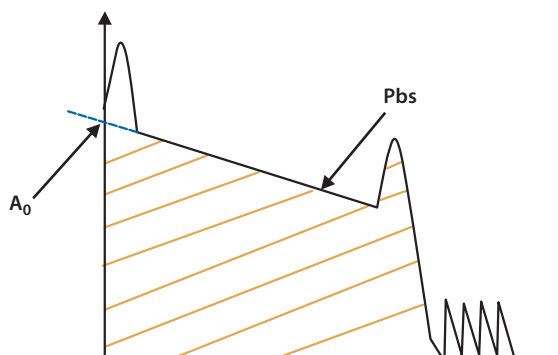


ORL measurement of a fiber link

In addition to providing a total link ORL result, the OTDR lets technicians locate and measure backreflection points. It also allows technicians to perform partial ORL measurements (according to a given fiber section).

Total ORL Measurement

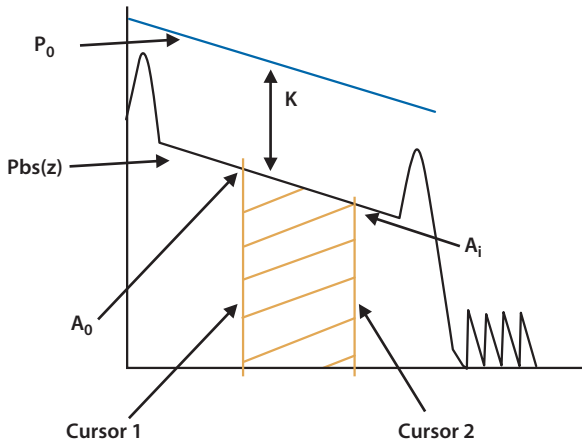
When performing an OTDR acquisition, total ORL is provided automatically and includes the reflected light caused by connectors and termination fibers. In order to remove consideration of the front-end connector reflectance at the incident power level (A_0), the backscattered level (Pbs) is extrapolated to the distance origin.



Total ORL measurement

Section ORL Measurement

It is also possible to measure ORL for a given section of the OTDR trace. Because the backscattered power level (Pbs) is known, the incident power A_0 at the starting point is referenced by cursor 1. Integration of the area between A_0 and A_i is performed, where A_i is the power level corresponding to the end of the ORL section located on the OTDR trace by cursor 2.



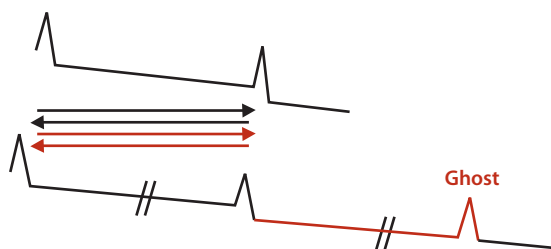
Section ORL measurement

4.4 Measurement Artifacts and Anomalies

Occasionally, the backscattered trace displays unexpected results and events.

4.4.1 Ghosts

False Fresnel reflections, termed ghosts, on the trace waveform may be occasionally observed. Ghosts can result from a strong reflective event on the fiber, causing a large amount of reflected light to be sent back to the OTDR, or an incorrect range setting during acquisition.

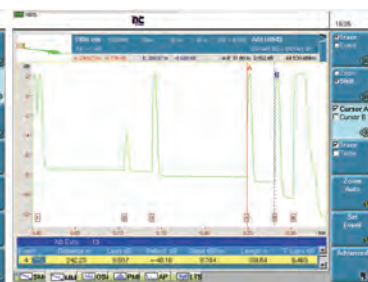


Ghosts on an OTDR trace

In both cases, the ghost can be identified because no loss is incurred as the signal passes through this event. In the first case, the distance at which the ghost occurs along the trace is a multiple of the distance of the strong reflective event from the OTDR.



Example of a ghost in the signal noise



Example of a ghost on the OTDR trace

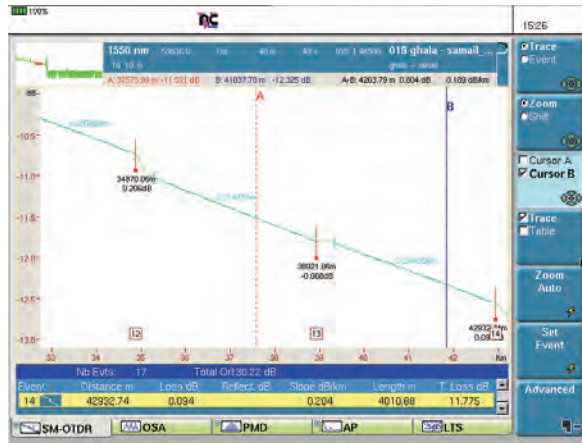
The use of index-matching gel at the reflection point can reduce the reflection. In addition, selecting a shorter pulse width, selecting a reduced power setting on the OTDR (some OTDRs provide this option), or adding attenuation in the fiber before the reflection can reduce the injected power.

If the event causing the ghost is situated at the end of the fiber, a few short turns around a suitable tool, such as a pen, pencil, or mandrel, will sufficiently attenuate the amount of light being reflected back to the source and eliminate the ghost. This technique is known as a mandrel wrap.

Be sure to select a mandrel of the appropriate diameter for the type of cable, jacketed fiber, or coated fiber used, eliminating permanent damage to the fiber span. Never bend a fiber or cable to introduce attenuation without using a suitable mandrel, which will prevent excess bending.

4.4.2 Splice Gain

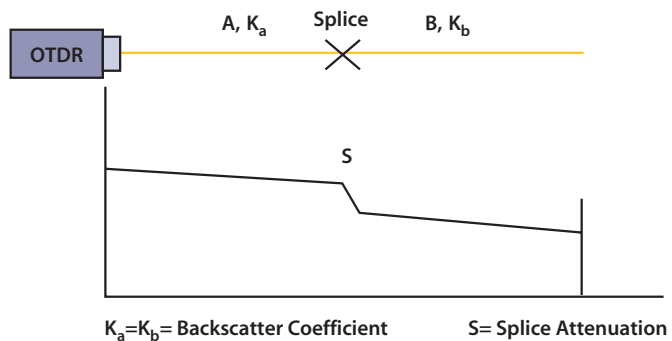
It is important to note that an OTDR measures splice loss indirectly, depending on information obtained from the backscattered signal. It is assumed that the backscattering coefficients of the fiber spans are identical all along the link under test. If this is not the case, then measurements can be inaccurate. One common example is the observance of apparent splice gains or gainers. The inaccuracy is quite small, but with today's fusion splicing equipment and experienced technicians making very low loss splices, it is possible for the effect to make the splice appear to be a gain instead of a loss.



A splice gain on an OTDR trace

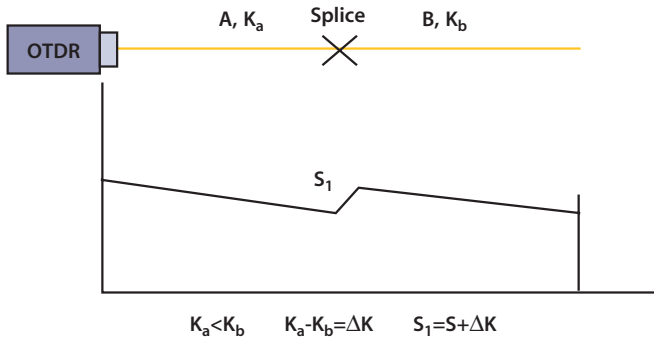
4.4.2.1 Splice Gain Theory

If fibers of different mode field diameters, such as core size, are joined, the resulting OTDR trace waveform can show higher backscattering levels. This result is due to the increased level of backscattered signal reflected back to the OTDR in the downstream fiber.

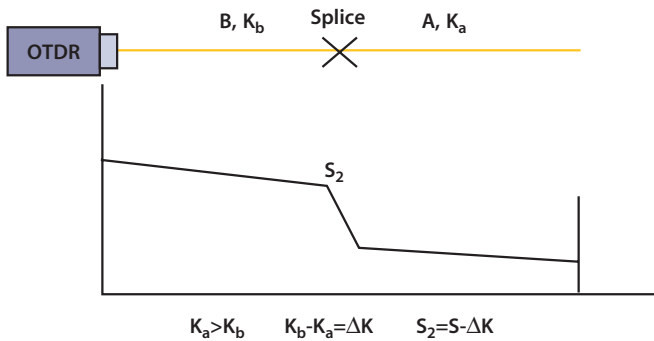


A normal splice

This phenomenon can occur when joining different types of fiber in a multimode span or joining two fibers with different backscatter coefficients.



A positive splice from A to B



A negative splice from B to A

The bidirectional or average splice loss value (S) can be calculated:

$$S = \frac{S_1 + S_2}{2}$$

4.5 Bidirectional Analysis

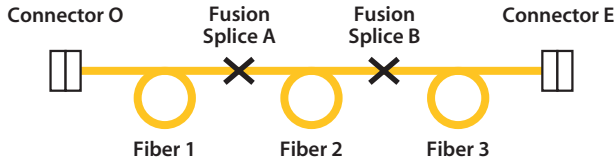
It is a known fact that passive amplifiers do not exist and that a gain in optical power cannot be obtained from a fusion splice; however, the OTDR will sometimes report a gain caused by differences in the backscatter coefficient. While these backscatter coefficient differences will not always cause a gain on the OTDR trace, they can still cause erroneous splice loss readings even if the reading is a loss.

Bidirectional analysis is a technique that is used to minimize the effects of backscatter coefficient differences along a span, which cause these erroneous splice readings. Use bidirectional analysis to achieve very accurate baseline data on a span, during acceptance testing, or when performing accurate measurement of splicing, often by subcontractors.

The concept of bidirectional analysis is as follows: If a backscatter coefficient mismatch exists between two spliced fibers, the algebraic sense of that difference will change depending on the direction of measurement. That is, when measured in one direction, the difference will appear as a gain; when measured in the opposite direction, the difference will appear as a loss. This difference will combine with the actual splice loss during measurement. However, averaging the splice loss reading taken in both directions subtracts out the backscatter effect, yielding the actual splice loss.

While the concept of bidirectional analysis is presented below in detail and with manual calculations, in actuality, this analysis is usually performed using software applications, such as JDSU FiberTrace or FiberCable. These software applications automatically perform bidirectional analysis on more complex spans than shown here.

4.5.1 Bidirectional Analysis of a Hypothetical Span



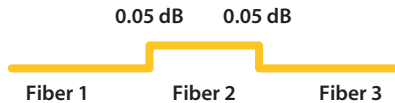
The span architecture

The hypothetical span consists of three fiber sections fusion-spliced between Connector O and Connector E. The relative backscatter profile of the fibers is shown below. In this example, the loss in the fiber is temporarily ignored in order to show that if the backscatter coefficient is sampled at many points along the span, the coefficient will be higher in the second, or middle, section.



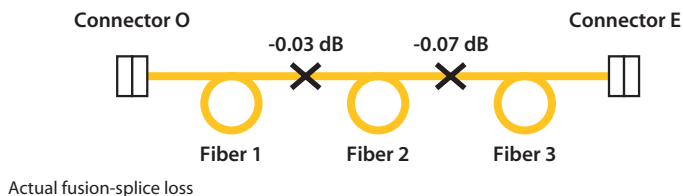
Backscatter profile of the span

For this example, the OTDR displays the effect of the backscatter mismatch as 0.05 dB. Note that the effect will appear as a gain when going into Fiber 2, but it will appear as a loss when exiting Fiber 2.

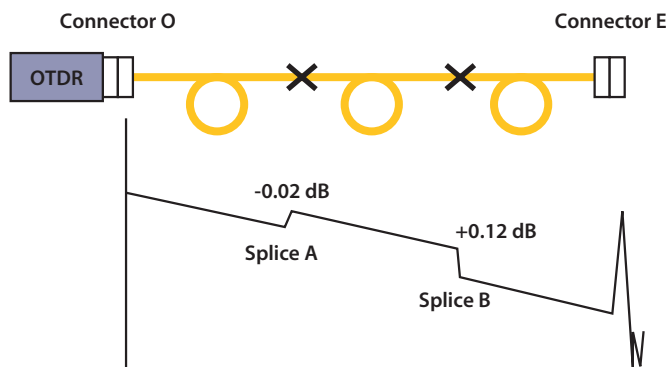


Apparent loss/gain at the junction due to the backscatter coefficient difference

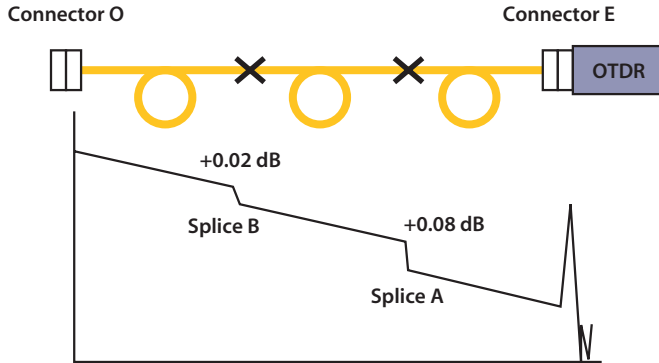
This span has been fusion-spliced, and the actual fusion-splice loss is -0.03 dB at splice A between Fibers 1 and 2 and -0.07 dB at Splice B between Fibers 2 and 3. For this discussion, a minus sign represents a loss and no sign represents a gain.



The following diagram shows what the OTDR reads:



When measuring from Connector O to Connector E with the fiber loss now shown, Splice A appears to be a gain of 0.02 dB (the actual -0.03 dB loss plus the apparent 0.05 dB gain due to backscatter). Splice B appears to be a -0.12 dB loss (the actual -0.07 dB loss plus the apparent -0.05 dB loss due to backscatter).



OTDR measurement from Connector E to Connector O (E→O)

The measurement is then repeated for the opposite direction (from Connector E to Connector O). Remember that Splice B is now on the left side of the OTDR trace, and Splice A is on the right side of the OTDR trace. In this case, Splice A appears to be a loss of 0.08 dB (the actual 0.03 dB loss plus the apparent 0.05 dB loss due to backscatter), and Splice B appears to be a 0.02 dB loss (the actual 0.07 dB loss plus the apparent 0.05 dB gain due to backscatter).

After performing the two measurements, a simple chart is generated, showing the loss and gain of Splices A and B in each direction. The two readings are added together, and the sum is divided by 2 in order to determine the average (actual) loss.

Bidirectional analysis table

	OTDR				Actual Loss
	O→E	E→O	Sum	Average	
Splice A	-0.02	0.08	0.06	0.03	0.03
Splice B	0.12	0.02	0.14	0.07	0.07

The results from the table now accurately represent the actual splice losses of the two events.

4.6 Getting the Most Out of Your OTDR

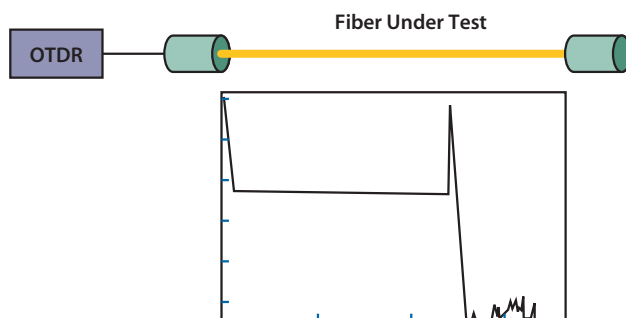
OTDRs are versatile tools that enable characterizing and troubleshooting any optical fiber link when you have all the cards in hand.

4.6.1 Using Launch Cables

Launch cables are accessories used typically with an OTDR for cable commissioning.

4.6.1.1 Acceptance Testing Without the Use of Launch and Receive Cables

The OTDR enables technicians to qualify components between both ends of a fiber link. However, neither the front-end connector nor the far-end connector can be qualified when the OTDR is directly connected to the link at the front end and nothing is connected at the far end. In this case, a reference backscattered signal is unavailable; so, loss measurements at the end connector points cannot be determined.



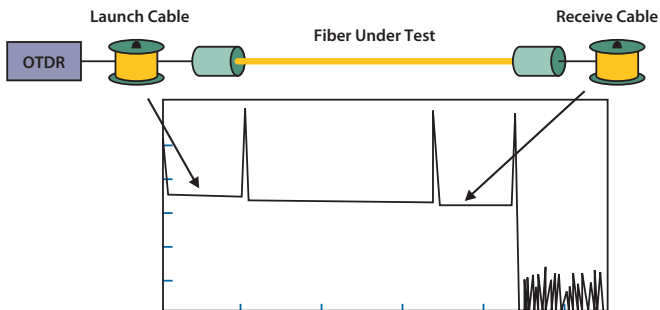
Acceptance testing without the use of launch and receive cables

In order to alleviate this problem, a section of cable is added at the OTDR launch location (front end) and at the receive location (far end) of the fiber under test.

4.6.1.2 Acceptance Testing Using Launch and Receive Cables

Launch and receive cables, consisting of a spool of fiber with a specific distance, can be connected to both ends of the fiber link under test to qualify the front-end and far-end connectors using an OTDR. The length of the launch and receive cables depends on the link being tested, but generally between 300 and 500 m for multimode testing and between 1000 and 2000 m for single-mode testing. For very long-haul fiber links, 4000 m of cable may be used. The fiber length is highly dependent on the OTDR attenuation dead zone, which is a function of the pulse width. The larger the pulse width, the longer the launch and receive cables.

In order to qualify the front-end and far-end connectors, connect the launch cable between the OTDR and the fiber under test, and connect the receive cable at the far end of the fiber link. The OTDR then characterizes the link including the launch and receive cables. Due to the additional fiber spools, measure a backscattered signal from both sides of the end connectors, allowing for loss and reflectance measurement of the front-end and far-end connectors; therefore, correctly qualifying the fiber link under test, as well as all of its components.



Acceptance testing using launch and receive cables

It is important to note that the fiber used in the launch and receive cable should match the fiber being tested, such as type and core size. In addition, the cable connectors should be of high quality.

The use of launch and receive cables in OTDR measurement allows for a number of effective tasks including:

- Correct measurement of the insertion loss of the link's far-end connectors
- Shifts the dead zone, caused by the OTDR front-end connector, outside of the trace from the link under test
- Improves modal equilibrium characteristics in multimode systems for more precise measurements
- Allows technicians to control the OTDR injection level into the link under test

4.6.2 Verifying Continuity

Sometimes when installing a multi-fiber cable, technicians must verify that the cable is continuous between the two exposed ends. They can perform an OTDR measurement on the cable in each direction, confirming continuity. Performing an OTDR measurement in one direction can determine the length of the cable as represented by the trace. However, the length of each fiber in the cable often varies by a few meters due to the slightly different buffer tube over lengths or the helix geometry of the fibers within the cable. It is difficult, if not impossible, to distinguish a fiber with a much lower over length from a broken fiber inside the cable, which is one meter from the far end.

An easier way to verify continuity, without having to perform a complete OTDR test from both ends, can be accomplished as follows. In this case, either access to both ends of the cable is required or two technicians with communications capability between them.

Connect the OTDR to one of the fibers in the cable (Fiber 1). Set the OTDR to Real Time mode, and observe the end of the resulting trace. If the length is grossly short, then the link is broken.

If the length looks approximately correct, then perform the following steps:

- If an end spike is not visible, indicating a reflective event at the non-terminated glass/air interface at the end of the cable, then one
-

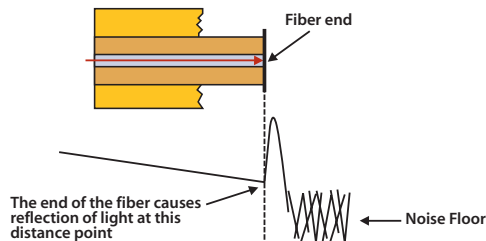
technician cleaves the fiber end squarely with a hand cleaver. The end spike or end reflection should become apparent. If it does not, the technician is not holding the end of Fiber 1. Fiber 1 must be broken somewhere inside the cable near the end.

- If, at first, a large end spike is visible, the technician dips the end of the fiber in index-matching gel or alcohol or wraps the fiber around a small mandrel near the end. Doing any of these tasks will attenuate the end spike. If it does not, then the fiber is broken somewhere else near the end of the cable.

4.6.3 Fault Location

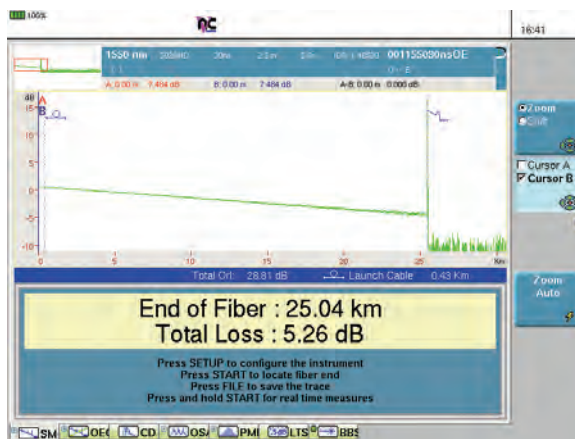
The OTDR can be an invaluable tool for fault location. Accurate fault location depends on careful measurement techniques using the OTDR and on complete and accurate system (cable) documentation. While entire courses are often taught on the subject of fault location, following the few recommendations discussed below may make the process more accurate and efficient.

Cable breaks can be partial or complete (catastrophic). The most common cause (over 40 percent) of cable breaks is an inadvertent dig-up. In the case of a dig-up, fault location does not need to be extremely precise because the damage can usually be easily located once technicians are near the break. Other types of breaks, including ballistic (from hunting weapons) or rodent damage, are more difficult to find, and accurate location with an OTDR can save significant time and money.



Break or fiber end location

When a cable is damaged, the resulting break may be highly reflective or non-reflective. It is generally much easier to determine an accurate distance to a reflective break. Therefore, it is sometimes helpful to measure several broken fibers until a reflective break is detected. If the break is non-reflective, it is usually best to let the OTDR's software determine the distance to the event using automatic analysis. This is because placing a marker visually can be inaccurate.



Fault location using an OTDR

In this case, the technician may want to calibrate the OTDR to display distance in cable or sheath distance by using an effective refractive index. While the OTDR can accurately determine distances to 5 meters in a 10,000 meter span, the helix factor of the cable can contribute up to 600 meters of inaccuracy over the span.

An alternate method of determining actual distance from optical distance is to measure the break from both end points and determine the position of the break relative to the total span length. This ratio of the optical distance to the break to the total optical length of the span will be the same as the ratio of the sheath distance to the break to the total sheath length.

It is important to remember the locations where cable slack is stored. If the OTDR reads 1800 meters to a break, but there are 200 meters of cable slack stored at an intermediate hand hole, manhole, or pole, then the distance to the break will be similarly shorter.

It is also important to remember that sagging in aerial plant sheath distance will differ somewhat from pole distance. After the location of the break is determined, it should be correlated to a cable sequential marking. Then, when excavating the cable or examining the aerial plant with binoculars, the correct section of cable can be confirmed quickly.

It is always best to measure the distance to the break from the last event whose physical location is known on the OTDR trace using the cursors. In this manner, the shortest possible measurement is performed by the OTDR, reducing the OTDR's contribution to measurement inaccuracy.

4.6.4 Effective Refractive Index

The OTDR determines the distance to the event based on time. The refractive index serves as a correlation factor between time and distance, allowing the OTDR to display distance accurately.

If the refractive index provided by the fiber manufacturer is known, the technician can set this value on the OTDR, thus improving the accuracy of the displayed optical distance.

In most cable designs, the length of the fiber is greater than the length of the cable. This can be caused by fiber over length in the buffer tubes (in loose buffer designs) or helixing of the buffer tubes or ribbons inside the cable. Therefore, the cable length or physical distance can vary significantly from the fiber length or optical distance.

In some cases, notably fault location, technicians may want the OTDR to display cable or physical distance instead of optical distance, which can be accomplished using a different value for the refractive index. This is sometimes termed the effective refractive index, which is adjusted for fiber over length.

There are two ways to determine the effective refractive index.

1. Using cable records or knowing the cable or physical distance (L_{eff}) between two known events on the OTDR trace, technicians can obtain the following data from the OTDR:
 - Optical distance between two known events (L_{opt})
 - Refractive index used by the instrument (RI_{opt})

The effective refractive index (RI_{eff}) can then be calculated using the formula:

$$RI_{\text{eff}} = (L_{\text{opt}} \times RI_{\text{opt}}) / L_{\text{eff}}$$

2. Some OTDRs, such as the JDSU T-BERD/MTS platforms, can calculate RI_{eff} automatically by delimiting the two known events with two cursors and changing the refractive index until the OTDR reports cable or physical distance instead of optical distance.

During initial cable documentation, it is recommended to use the OTDR features that permit the addition of notes to events or files. Entering geographic or GPS data will be very useful during fault location. Again, there is absolutely no substitute for complete, detailed, accurate cable documentation records during fault location.

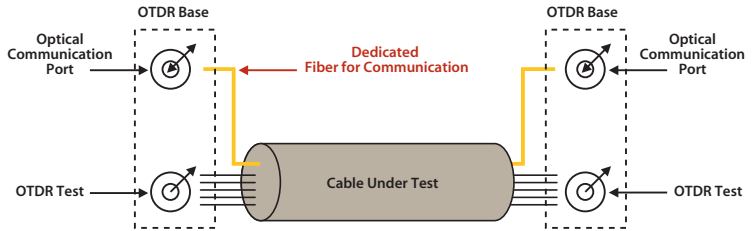
4.6.5 Automating Bidirectional Analysis

Testing time increases with the number of fibers. In order to expedite the installation phase or increase the number of fibers tested within a given time period, having fully automatic tools, such as an automatic bidirectional OTDR tester, becomes ever more important.

The automatic bidirectional OTDR function solves the problems of traditional bidirectional OTDR analysis. An automatic solution provides the following capabilities:

- Performs a fiber continuity check to ensure that both units are testing the same fiber
- Provides error-free operation by exchanging the master unit's OTDR test configuration if different from that of the slave unit
- Performs data acquisition on the slave unit and transfers the trace to the master unit
- Performs data acquisition on the master unit and transfers the trace to the slave unit
- Performs bidirectional measurements on both units
- Stores results in a single file or in two files

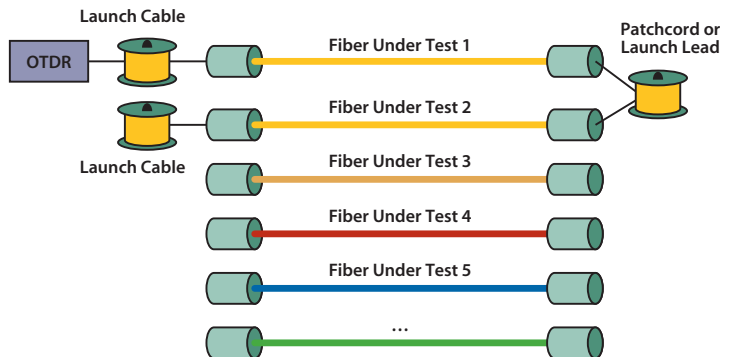
The bidirectional analysis procedure is fully automatic, and all of the test results are immediately accessible on both units. In addition, unprecedented data acquisition speeds and fully automatic bidirectional capabilities significantly reduce test times.



Automatic bidirectional OTDR measurement configuration

4.6.6 Loopback Measurement Method

Using the loopback method, technicians need only one OTDR for bidirectional OTDR measurements. The OTDR data acquisitions are performed at one end of the fiber (the near end). Being able to measure two fibers with one acquisition reduces the data acquisition time by a factor of two. One technician is required at the near-end OTDR location while the other technician, located at the far end of the link, loops the fiber path with a splice, patchcord, or launch lead.



A loopback measurement, measuring O→E of fiber 1 and E→O of Fiber 2

Because the end customer of the cable is more interested in the precise loss results (without the fiber loops) rather than the test method, the report contains only the cable data and eliminates the splice point, patchcord, or launch lead from the result tables.

4.7 OTDR Acceptance Reporting Tool

Data collected in the field for analysis must be organized in order to generate the acceptance report. The acceptance report provides the end customer with an easy-to-read professional report and documents the characteristics of the fiber. Technicians organize the results into dedicated tables, including cable and job information, section length, bidirectional splice loss, end connector reflectance, insertion loss, end-to-end loss, wavelength loss comparison, and out-of-range loss values.

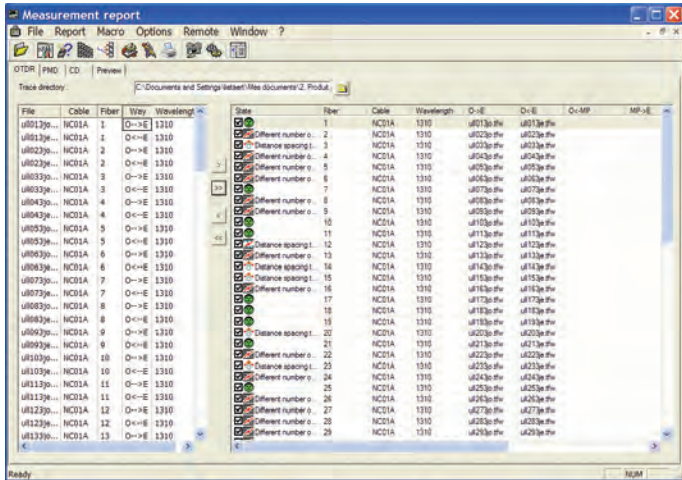
The OTDR report generation process requires four steps: results analysis, results conditioning, report generation, and document printout.

4.7.1 Results Analysis

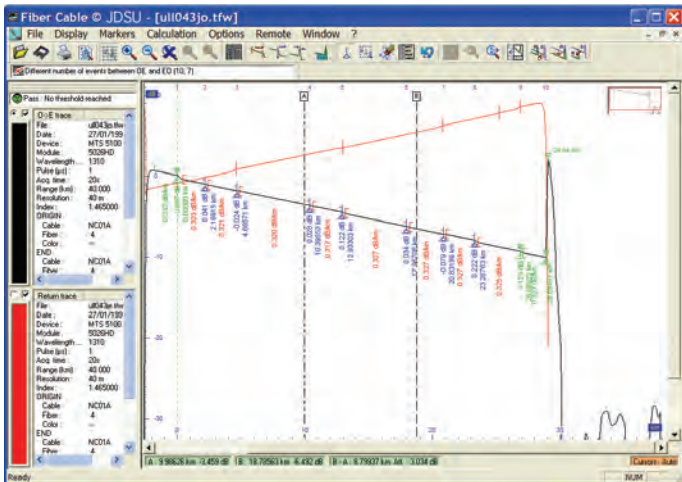
Test results are downloaded and organized in the office computer. With direct access to the OTDR traces, the acceptance reporting software automatically combines the O→E and E→O traces for each fiber at each wavelength.

Technicians follow a simple trace information convention using the same cable ID and fiber numbers. O→E indicates one direction. E→O indicates the other direction. On one screen, technicians can access all of the bidirectional analysis data collected on the fibers for the entire cable.

Using the data from the OTDR traces in both directions, enables event locations to be adjusted on the fiber creating a template.

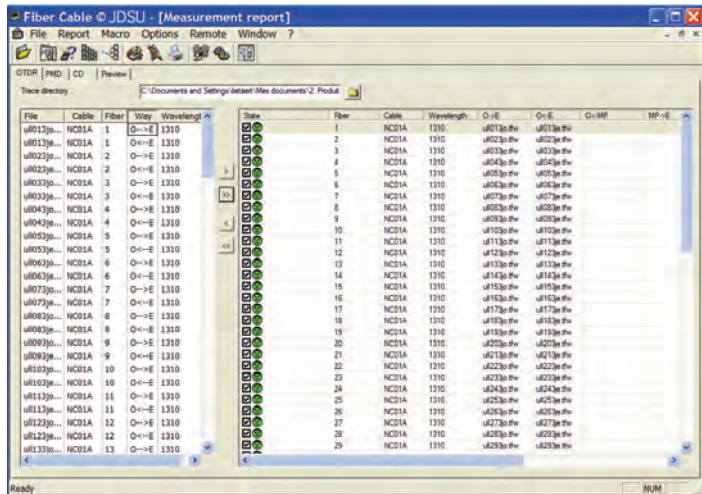


Test results management using JDSU FiberCable software



Bidirectional analysis using JDSU FiberCable software

This template is then used as a reference for all the other fibers in the cable, thus ensuring that the splice points are correctly located and recorded for the entire cable. An update of the bidirectional analysis status prevents incorrect results.



The template is applied to all the fibers using JDSU FiberCable software

Technicians may want to include textual information, for fault finding and cable restoration purposes, along with the fiber template. Each event can be identified with a descriptor (manhole, water crossing, bridge, GPS coordinates, or other physical landmark) for identification. This information must only be entered once into the template where it can then be copied to all of the other fibers in the cable.

4.7.2 Results Conditioning

After completing the bidirectional test data at both or multiple wavelengths for all of the fibers, the results must be compiled into cable records. Using the traditional method, this operation took the longest in the process, because all of the data had to be exported into a spreadsheet and formatted into a table.

When processing such a large amount of test data, it is important to verify the results before running the report. A report preview function may be available, which is useful in displaying the individual fiber data compiled into table format. Technicians can then step through each fiber, display the OTDR traces and the table of events, and preview the data entry in spreadsheet format.

ID	Cable ID	Fiber	Wavelength	Average	1 : O→H	1 : E→H	1 : Average	2 : O→H	2 : E→H	2 : Average	3 : O→H	3 : E→H	3 : Average	4 : O→H	4 : E→H	4 : Average
NC...	1	1310	0.033	0.256	-0.041	C	0.107	0.013	0.018	0.015	0.056	-0.003	0.026	0.046	0.028	0.0
NC...	2	1310	0.021	0.285	0.028	C	0.157	0.019	0.012	0.015	0.035	0.029	0.032	0.026	0.026	0.0
NC...	3	1310	0.027	0.331	-0.012	C	0.159	0.010	0.010	0.010	-0.010	0.035	0.012	0.016	0.038	0.0
NC...	4	1310	0.023	0.365	-0.059	C	0.153	0.038	0.012	0.025	-0.026	0.188	0.061	0.003	0.001	0.0
NC...	5	1310	0.023	0.184	0.103	C	0.143	0.046	0.050	0.048	0.171	-0.125	0.023	0.007	0.006	0.0
NC...	6	1310	0.045	0.376	-0.157	C	0.110	0.047	0.035	0.041	-0.041	0.071	0.015	0.072	0.085	0.0
NC...	7	1310	0.031	0.137	-0.010	C	0.063	0.007	0.018	0.012	0.073	-0.038	0.018	0.028	0.053	0.0
NC...	8	1310	0.026	0.473	-0.094	C	0.234	-0.010	-0.003	-0.007	-0.081	0.106	0.012	0.123	0.125	0.1
NC...	9	1310	0.015	0.238	-0.015	C	0.112	0.013	0.013	0.013	0.046	0.025	0.025	0.031	0.043	0.0
NC...	10	1310	0.022	0.469	0.228	C	0.348	0.016	0.021	0.016	0.004	0.025	0.015	-0.004	0.026	0.0
NC...	11	1310	0.031	0.384	0.121	C	0.252	0.043	0.040	0.041	0.071	-0.031	0.020	0.026	0.022	0.0
NC...	12	1310	0.028	0.372	-0.050	C	0.161	0.065	0.059	0.062	-0.081	0.082	0.001	0.062	0.059	0.0
NC...	13	1310	0.028	0.517	0.032	C	0.175	0.085	0.079	0.082	-0.054	0.071	0.008	0.107	-0.038	0.0
NC...	14	1310	0.035	0.372	0.101	C	0.237	0.009	0.016	0.012	0.035	0.004	0.020	-0.041	0.047	0.0
NC...	15	1310	0.023	0.520	0.169	C	0.359	-0.009	0.006	-0.001	-0.003	0.047	0.022	0.057	0.037	0.0
NC...	16	1310	0.026	0.400	-0.025	C	0.187	0.018	0.016	0.017	-0.015	0.076	0.031	-0.018	0.050	0.0
NC...	17	1310	0.022	0.134	0.069	C	0.101	0.024	0.030	0.031	0.100	-0.025	0.037	0.106	-0.073	0.0
NC...	18	1310	0.024	0.407	-0.153	C	0.127	0.082	0.071	0.076	-0.129	0.193	0.032	-0.015	0.098	0.0
NC...	19	1310	0.033	0.381	0.237	C	0.309	-0.003	0.021	0.009	0.131	-0.047	0.042	0.053	0.015	0.0
NC...	20	1310	0.022	0.470	-0.019	C	0.226	-0.007	-0.001	-0.004	-0.049	0.115	0.033	0.088	-0.009	0.0
NC...	21	1310	0.011	0.388	0.112	C	0.239	-0.001	0.003	0.001	0.056	-0.010	0.023	0.047	-0.046	0.0

Report preview using JDSU FiberCable software

4.7.3 Report Generation

After compiling, previewing, and verifying results against specific criteria, the next step is to generate the report using a spreadsheet program. Technicians select the various required tables for the acceptance report.

- Cable and job information
- Section length
- Bidirectional splice loss
- End connector reflectance and insertion loss
- End-to-end loss
- Insertion loss (with a loss test set)
- Optical return loss (with a loss test set)
- 1310/1550 nm loss comparison
- Out-of-range loss values

4.7.4 Document Printout

Although the data produced at this stage is complete, to transform the results into a professional-looking cable report requires more work.

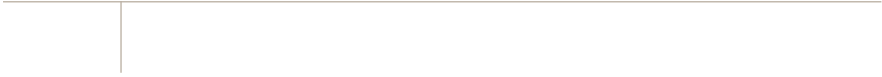
Technicians can use loss comparison tables between wavelengths and out-of-range loss values summary tables to identify and point out potential problems during installation, either through mechanical stress (1310/1550 nm loss comparison) or through non-conformity to the cable acceptance criteria.

At this point, technicians can add information and comments regarding the cable, fiber, and test parameters before printing the final document. This level of document customization provides technicians with the ability to better report the data to the end customer.



Glossary

Chapter 5



ADM	Add/Drop Multiplexer
ADZ	Attenuation Dead Zone
APC	Angled Physical Contact
APD	Avalanche Photodiode
ASE	Amplified Spontaneous Emission
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
BR	Back Reflection
BW	Bandwidth
C-Band	Conventional Band
CD	Chromatic Dispersion
CNR or C/N	Carrier-to-Noise Ratio
CW	Continuous Wave
CWDM	Coarse Wavelength Division Multiplexing
dB	Decibel
DCF	Dispersion-Compensating Fiber
DCM	Dispersion-Compensating Module
DCU	Dispersion-Compensating Unit
Demux	Demultiplexer
Dense WDM	Dense Wavelength Division Multiplexing (See DWDM)
DFB	Distributed Feedback Laser
DST	Dispersion-Supported Transmission
DUT	Device Under Test
DWDM	Dense Wavelength Division Multiplexing
E-Band	Extended Band
EDFA	Erbium Doped Fiber Amplifier
EDZ	Event Dead Zone
ELED	Edge-Emitting Light-Emitting Diode
E/O	Electrical-to-Optical Converter

EMD	Equilibrium Mode Distribution
FBGs	Fiber Bragg Gratings
FC	Fixed Connection
FP	Fabry-Perot
FTTC	Fiber-to-the-Curb
FTTN	Fiber-to-the-Node
FTTH	Fiber-to-the-Home
FTTP	Fiber-to-the-Premises
FTTx	Fiber-to-the-x
FUT	Fiber Under Test
FWHM	Full Width Half Maximum
FWM	Four Wave Mixing
GRIN	Gradient Index
HCS	FiberHard-Clad Silica Fiber
HFC	Hybrid Fiber Coax
IDP	Integrated Detector/Preamplifier
IIN	Interferometric Intensity Noise
ILD	Injection Laser Diode
InGaAs	Indium Gallium Arsenide
InGaAsP	Indium Gallium Arsenide Phosphide
InP	Indium Phosphide
IR	Infrared
IREDD	Infrared Emitting Diodes
L-Band	Long Wavelength Band
LD	Laser Diode
LEAF	Large Effective Area Fiber
LED	Light Emitting Diode
MFD	Mode Field Diameter
MM	Multimode
MMF	Multimode Fiber

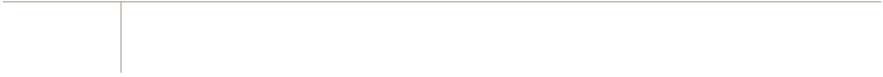
MQW	Multi-Quantum Well
MRN	Multiple Reflection Noise
MUX	Multiplexer
NA	Numerical Aperture
NDSF	Non-Dispersion-Shifted Fiber
NEXT	Near-End Crosstalk
NZ-DSF	Non-Zero-Dispersion Shifted Fiber
OADM	Optical Add/Drop Multiplexer (ADM)
O-Band	Original Band
OCH	Optical Channel
OCWR	Optical Continuous Wave Reflectometer
ODC	Optical Directional Coupler
ODN	Optical Distribution Network
O/E	Optical to Electrical
OLT	Optical Line Termination
OLTS	Optical Loss Test Set
OMS	Optical Multiplex Section
ONI	Optical Network Interface
ONT	Optical Network Termination
ONU	Optical Network Unit
OOI	Open Optical Interface
ORL	Optical Return Loss
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal-to-Noise Ratio
OTDR	Optical Time Domain Reflectometer
OXC	Optical Crossconnect
PC	Physical Contact or Polished Contact
PCS Fiber	Plastic Clad Silica fiber
PD	Photodiode
PFM	Polarization Maintaining Fiber

PMD	Polarization Mode Dispersion
RIN	Relative Intensity Noise
S-Band	Short Wavelength Band
SBS	Stimulated Brillouin Scattering
SC connector	Subscription Channel connector
SE	Slope Efficiency
SLED	Surface Light Emitting diode
SLM	Single-Longitudinal Mode Laser
SM	Single Mode
SMLD	Single-Mode Laser Diode
SMF	Single-Mode Fiber
SNR or S/N	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifier
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
ST Connector	Straight Tip Connector
TICL	Temperature-Induced Cable Loss
U-Band	Ultra-Long Wavelength Band
UV	Ultraviolet
VCSEL	Vertical Cavity Surface-Emitting Laser
VECSEL	Vertical Extended Cavity Surface-Emitting Laser
VFL	Visual Fault Locator
WDM	Wavelength Division Multiplexing
XC	Crossconnect
XPM	Cross-Phase Modulation
XT	Crosstalk



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Chapter 6



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