SMPTE ENGINEERING GUIDELINE

Guide to SMPTE ST 297 Optical SDI Networks

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Foreword

SMPTE (the Society of Motion Picture and Television Engineers) is an internationally-recognized standards developing organization. Headquartered and incorporated in the United States of America, SMPTE has members in over 80 countries on six continents. SMPTE's Engineering Documents, including Standards, Recommended Practices, and Engineering Guidelines, are prepared by SMPTE's Technology Committees. Participation in these Committees is open to all with a bona fide interest in their work. SMPTE cooperates closely with other standards-developing organizations, including ISO, IEC and ITU.

SMPTE Engineering Documents are drafted in accordance with the rules given in Part XIII of its Operations Manual.

SMPTE EG 2069 was prepared by Technology Committee 32NF.

Intellectual Property

At the time of publication no notice had been received by SMPTE claiming patent rights essential to the implementation of this standard. However, attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. SMPTE shall not be held responsible for identifying any or all such patent rights.

Introduction

International standards for the real-time transmission of video, audio, data and metadata over optical digital interfaces have been in existence for a number of years. SMPTE ST 297 standardizes the requirements for a "*Serial Digital Fiber Transmission System for SMPTE ST 259, SMPTE ST 344, SMPTE ST 292-1 and SMPTE ST 424 Signals*" which cover all SMPTE SDI rates up to and including 3 Gb/s.

The design, installation, setup and evaluation of an optical digital interface used in professional broadcast applications, differs from a typical coax (copper), digital interface and from optical interfaces used in datacom / telecom enterprise or carrier systems.

Different optimizations in the network components used for optical connectivity for SDI interfaces must be considered in order to ensure a robust, reliable Optical digital network.

This Engineering Guideline outlines the key components of an optical digital Interface developed in accordance with SMPTE ST 297.

It documents methods and best practice for the design, installation, setup and evaluation of SMPTE ST 297 optical digital interfaces, and illustrates how the robustness of an optical SDI link can be evaluated.

1 Scope

This engineering guideline provides guidance on the implementation of SMPTE ST 297 optical SDI networks in the following areas:

Network:

- Basics components of an optical network
- Multimode versus Single mode fiber
- Link budget – how to calculate, important factors
- Differences between Optical SDI interfaces and components and datacom interfaces and components
- Issues arising from the use of non-optimized ST 297 optical components
- Optical attenuators – why are they required and when to use them
- Optical isolators – why are they required and when to use them

Evaluation of an optical system and its components:

- Test and measurement equipment
- Test and measurement methodology
- Important test parameters
- Ensuring interoperability

2 Optical SDI Networks

As broadcasters upgrade their facilities to support the carriage and distribution of higher frame rate formats such as 1080p50/60; image formats with increased dynamic range such as 12-bits for digital cinema; the carriage of stereoscopic 3D image formats; "Quad-Full HD" images etc, an increasing number of fiber optic systems are being deployed. Fiber based systems offer a number of advantages over coax based systems, including high performance over long link distances, virtually unlimited bandwidth, reduced sensitivity to electrical interference and smaller lighter trunking. To deploy a robust optical network, careful selection and evaluation of the components is required.

2.1 Optical Components

A basic optical transmission system consists of several components illustrated in the block diagram shown in Figure 1. The main components are:

a) transmitter, containing the optical source and a means of modulating the optical output from the source with the signal to be transmitted;

b) the transmission medium; in this case, the optical fiber;

c) a receiver, containing the photo-detector which converts the received optical power back into the electrical waveform;

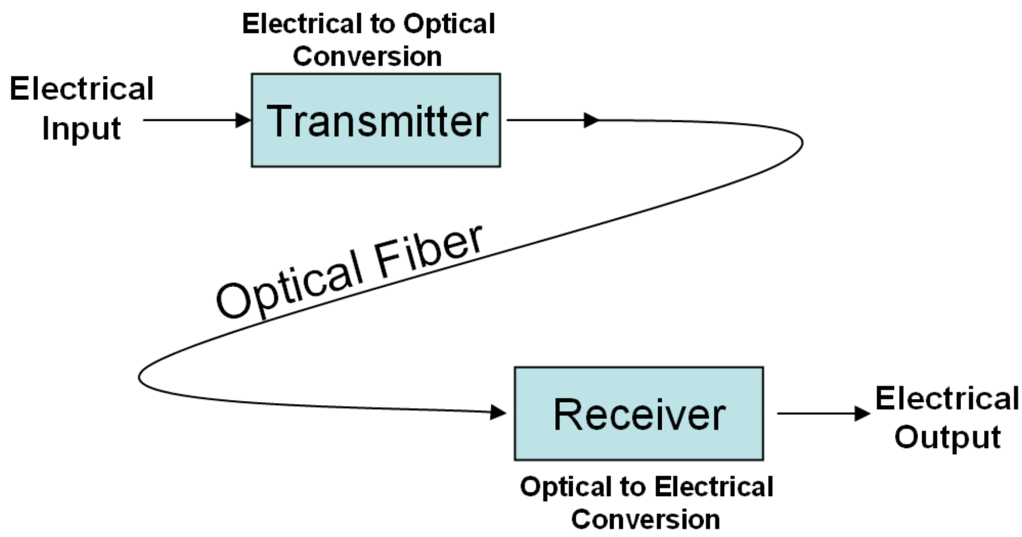


Figure 1 – Basic Optical Transmission System

The following sections explore the main components of an optical transmission system as well as the different form factors used in a typical deployment.

2.1.1 Transmitters

Optical transmitters are devices that include an optical source and signal conditioning electronics to inject a signal into a fiber. The type of optical source used in the transmitter will affect the performance and ultimately the distance a signal can travel within the fiber. Although several types of optical sources have been (and are still used), in data transmission, lasers are the predominant sources in optical SDI transmitters. See Annex A for more details on transmitter design.

2.1.1.1 Lasers

Lasers are predominantly used as sources in an optical transmission system. LASERs, an acronym — Light Amplification by the Stimulated Emission of Radiation — produce a coherent light with a narrow spectral width through, as the name implies, stimulated emission.

Applying current to a semiconductor laser excites electrons to produce photons with a very specific wavelength and phase. These photons collect in a cavity where they reflect off opposing mirrors to travel back and forth through the lasing medium. In the process, they stimulate other electrons and can cause the emission of more photons of the same wavelength and phase. A cascade effect occurs, resulting in the propagation of many photons of the same wavelength and phase. Coherent light is emitted from two opposite faces. The front face couples to an optical fiber, while the back face is often used for power monitoring.

The wavelengths and modes of light are determined by the makeup of the semiconductor materials and the size of the optical cavity.

In SMPTE ST 297, Optical transmitters are separated into 3 main categories: Low-power (short haul), Medium-power (medium haul), and High-power (long haul). To achieve these different link distances, different laser types with different characteristics are commonly used. Table 1 provides a comparison of typical laser types, their usage and advantages / disadvantages.

Table 1 – A comparison of optical sources

	VCSELs	FP Laser	DFB Laser
Typical Link Distances	200m – 400m	10km – 30km	30km – 80km
Cost	Low cost	Mid cost	High cost
Advantages	Typically used in lower cost, lower power multimode installations	Ideal for low cost point to point on single mode fiber	Used for medium and long haul applications, as well as in wavelength division multiplexing
Disadvantages	Shorter link distance over multimode fiber	Not suitable for wavelength division multiplexing, dispersion limited at high data rates	High cost

Each laser type has different characteristics that impact the performance of the optical transmitter. The laser type, and thus the transmitter, is generally selected based on link distance, however, there are many other parameters to be considered when selecting a transmitter for optical SDI transmission. The following sections discuss in more detail the different laser types and their unique properties.

2.1.1.2 VCSELs

Vertical-cavity surface-emitting lasers (VCSELs) are laser sources with a monolithic laser resonator, where the emitted light leaves the device in a direction perpendicular to the chip surface.

Because the light is emitted from the surface of the device and not from the edge as in other semiconductor laser types, tens of thousands can be fabricated simultaneously on a semiconductor wafer significantly reducing the cost. VSCELs have lower output powers and a wider spectral width than their FP (Fabry-Perot) and DFB (Distributed Feed Back) cousins, and are generally used for applications that require transmission over hundreds of meters rather than 10’s of kilometers.

VCSELs typically emit light in the 650 nm to 1300 nm wavelength region.

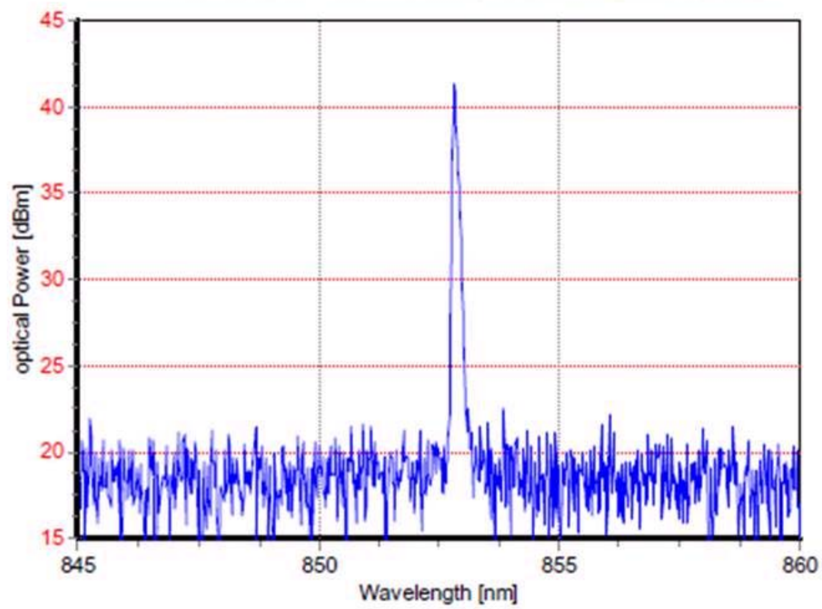


Figure 2 – VCSEL spectrum

2.1.1.3 Fabry-Perot Lasers

Fabry-Perot (FP) Lasers are well suited for the propagation of information over fiber. They are capable of high output powers, have an output beam with a narrow angular spread which allows increased coupling efficiencies to single mode fiber and can be modulated directly at high frequencies.

The Fabry-Perot laser is the predominant laser found in medium haul optical SDI transmitters today. These transmitters are configured to meet SMPTE ST 297 Medium-power transmitter specifications usually with output power in the range of -5 dBm to 0 dBm.

In this type of laser, a relatively broad wavelength spectrum of light is emitted as shown in Figure 3. Each peak is a mode that resonates within the cavity with a spectral width ranging from 2-4 nm (RMS)

The different wavelengths of light emitted by the FP laser, travel along the fiber at different speeds. This causes a spreading of the pulse of light over the length of the fiber. Eventually, the spreading of different wavelengths can overlap neighboring pulses.

This is known as dispersion and limits the distance the pulse can travel in the fiber. The effects of dispersion are discussed further in Section 4.1.2.2.

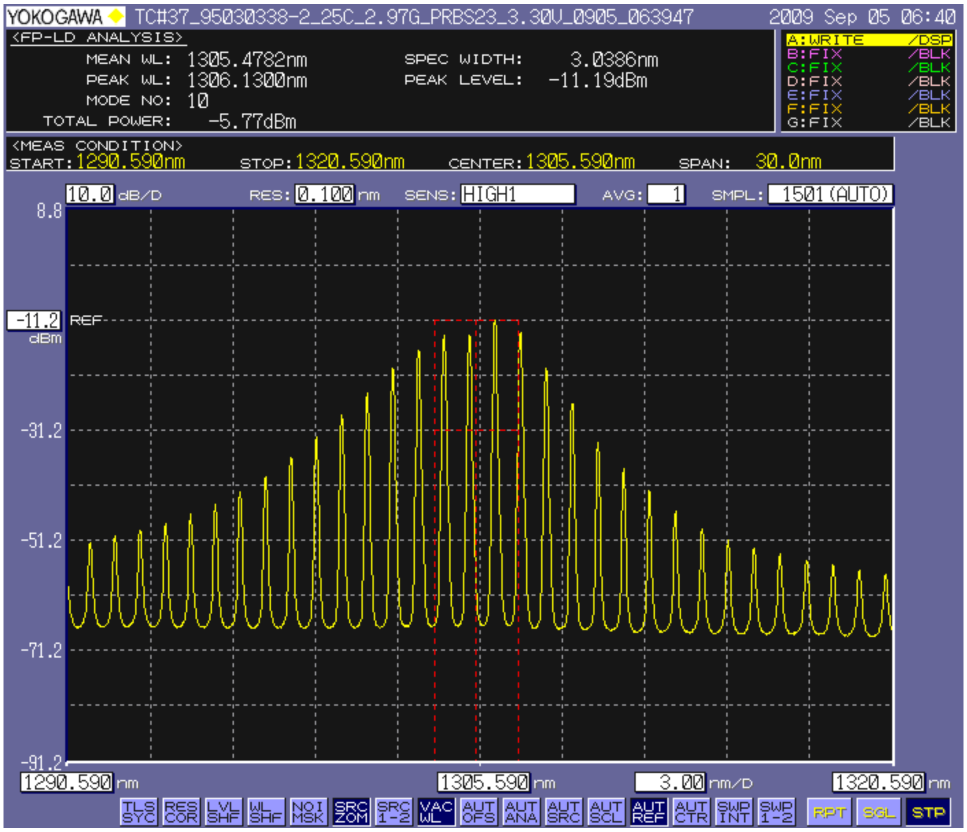


Figure 3 – FP spectrum

2.1.1.4 Distributed Feedback Laser (DFB)

A DFB laser is similar to an FP laser, but with a diffraction grating within the device which acts as an optical filter that selects a single wavelength with a tighter spectral width than is possible with an FP laser as seen in Figure 4.

This results in longer transmissions over an optical fiber due to the reduced dispersion effect of the single wavelength and tighter spectral width of the DFB laser. The DFB laser is used in long haul transmitters as well as CWDM transmitters as discussed in Section 5.

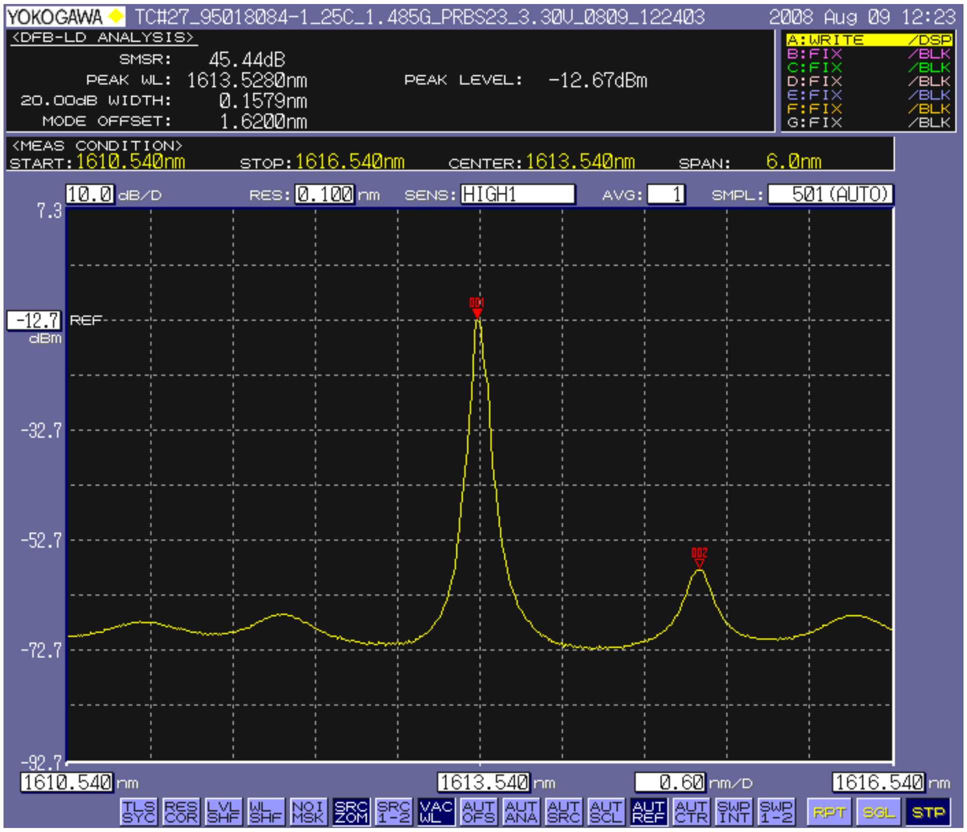


Figure 4 – DFB spectrum

2.1.2 Receivers

As a signal travels along a fiber, degradation will occur (more on this in Section 4). Optical receivers extract the information that has been placed on the modulated light carrier by the distant transmitter and restores the information to its original form. The signal arriving at the receivers is typically at a lower power than the power at which it was originally launched by the transmitter. The minimum power at which the receiver can detect and decode the signal is given by the receiver sensitivity.

SMPTE ST 297 specifies receiver sensitivities of -17 dBm for SMPTE ST 424 signal rates (3 Gb/s nominal). That is, the receiver is able to detect and restore a signal arriving at the receiver with an optical power of -17 dBm with a bit error ratio of less than 10^{-12}.

When selecting a receiver, it is also important to ensure that there is no additional sensitivity penalty for SDI pathological signals if the over all system power will be close to the receiver sensitivity specification

A simple receiver is made of a photo-detector, a Transimpedance Amplifier (TIA), and a limiting amplifier. See Annex B for more details on receiver design.

Overall system performance is heavily influenced by the optical sensitivity of the receiver. The types of optical detectors and quality of the TIA selected must be appropriate for the application.

In all communication equipment there are two types of optical detectors used; the PIN photodiode and the APD photodiode.

The PIN (Positive-Intrinsic-Negative) diode is a very small device (~200 um x 200 um) which has a low bias voltage, is economical, and provides receiver sensitivities around -20 dBm.

The Avalanche PhotoDiode (APD) is more complex, larger, requires a large bias voltage, is much more expensive, but does result in a sensitivity of -30 dBm.

An APD based receiver is typically used for long links where the input power at the receiver is low.

Both PIN based receivers and APD based receivers are in use in optical SDI links for broadcast video applications, but PIN based receivers are most prevalent mainly due to the lower cost.

2.1.3 Optical Isolators

All lasers are susceptible to back reflection.

Whenever there is a change in refractive index, back reflection — or as it is sometimes called, optical return loss (ORL) — will occur. ORL is a phenomenon whereby a fraction of the transmitted optical power is reflected back toward the source.

Splices, patches and defects in the fiber can all cause back reflections and these back reflections create undesirable effects that impact signal integrity and hence the link distance over which data can be successfully recovered without error.

SMPTE ST 297 (Section 3.6.2) specifies a minimum return loss of 20 dBm on multimode fiber, and 26 dBm on single mode fiber.

Fiber with more than 20 dB of return loss (back reflection), is considered quite high. Optical isolators can be used on laser sources where a return loss of 20 dB or more is expected.

An isolator is an optical component which allows the transmission of light in only one direction. Light propagates through the isolator in the forward direction while light propagating in the reverse direction is absorbed or displaced.

An optical Isolator protects laser sources from back reflections and signals that can cause instabilities and damage, thereby improving the signal to noise ratio for laser diode based transmitters.

Isolators are available in both polarization-dependent and polarization-independent models throughout the 770 to 2010 nm wavelength range. High power fiber isolators are built using a specialized fiber end face process to increase power handling capabilities. A minimum of 1 m of fiber is included on both sides of each fiber isolator.

Figure 5 – Optical Isolator

2.1.4 Optical Attenuators

As discussed in Section 2.1.2, the receiver sensitivity is the lowest power at which the receiver can recover a signal and is specified in the receiver datasheet. Another critical parameter is the receiver overload specification. The overload specification is the highest power at which the receiver will recover a signal without error.

Many transmitters on the market have a specified launch power of 0 dBm or higher. For short fiber links, a receiver with low overload levels together with a transmitter with higher launch power can place the link in jeopardy creating bit errors or even receiver damage. To ensure the optical link will be robust, a receiver with an adequate overload level must be selected.

SMPTE ST 297 recommends a minimum overload power of 0 dBm, however many receivers have an overload specification lower than this. Where it is not possible to select a receiver with sufficient overload levels to accommodate the system transmit power, an optical attenuator can be used to protect the receiver.

An optical attenuator is a device used to reduce the power level of an optical signal. Commonly used fiber optic attenuators are the female to male type, which is also called a plug fiber attenuator.

Types of attenuators:

- Fixed value fiber optic attenuators can reduce the optical light power at a fixed level, for example, a 5 dB LC UPC fiber optic attenuator

- Variable fiber optic attenuators are with adjustable attenuation range.

- There are also attenuation fiber optic patch cables available, their function is the same as attenuators and are used inline.

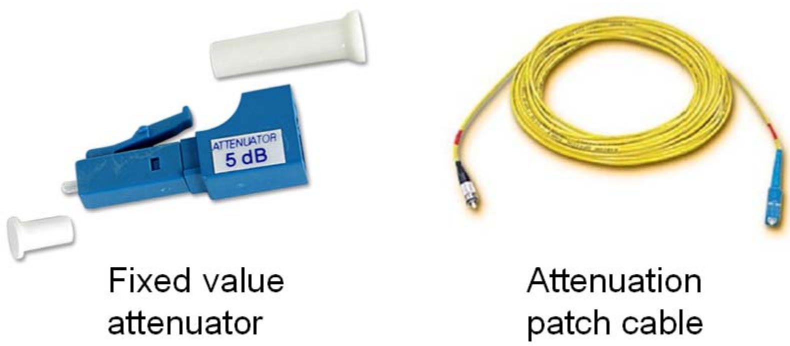


Figure 6 – Attenuator types

The IEC have published a Technical Report (IEC/TR 60825-17) highlighting large variations and wavelength dependent variations in the attenuation specified by the manufactures. Mechanical variations have also been noted and some plug style attenuators can damage the connectors to which they are fitted. It is recommended that active transceivers with fixed ferrules must never be connected with a plug style connector. Although the published report focuses mainly on the SC plug style fixed attenuators, an evaluation of the attenuators is recommended prior to employing them in a system.

2.1.5 Optical Splitters

Optical splitters (also called couplers), take an optical signal and split it into two or more outputs, similar to the operation of a distribution amplifier. Optical splitters are passive optical components that can divide (or combine) light power between multiple fibers. There are many types of couplers available; the most commonly used are the 50/50, 80/20 and the 90/10. The numbers designate the percentage of optical power divided between the outputs.

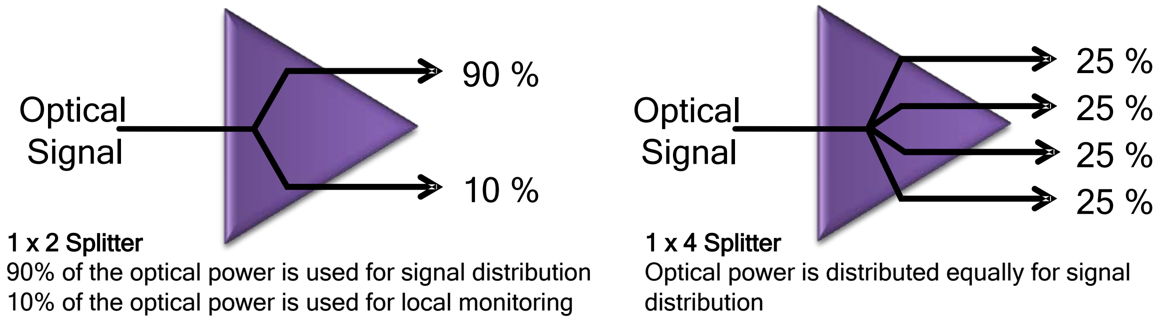


Figure 7 – Two examples of optical splitters.

Splitters are bi-directional and can also be used to combine multiple optical signals (of different wavelengths), on to a single fiber, but introduce loss in the system when used this way.

2.1.6 Patch Panels

Fiber optic patch panels are commonly used in a fiber optic management unit. When installing and managing fiber optic links, hundreds or even thousands of fiber optic cables and cable connections can be installed.

Fiber optic management products are used to offer space and protection for the fiber cables and cable links, and they make it easier to manage and troubleshoot the installation.

There are two types of patch panels typically used in the fiber optic management unit:

2.1.6.1 Rack Mount Fiber Optic Patch Panel

Rack mount fiber optic patch panels are used to terminate and distribute optical fiber cables, and offer a convenient way to organize and connect the fiber optic links.

2.1.6.2 Wall Mount Fiber Optic Patch Panel

Wall mount fiber optic patch panels use fiber optic adapters, fiber optic pigtails and patch cables, to realize the function of optical fiber distribution. They are also used for protective connections for the fiber cables and pigtails. Wall mount fiber patch panels are mainly used in fiber optic cabling and user terminal applications.

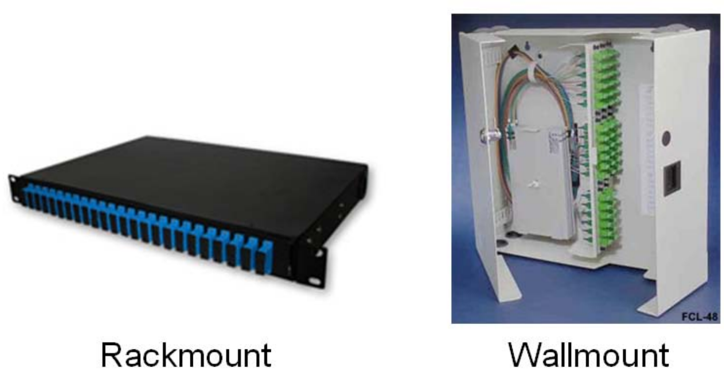


Figure 8 – Examples of Patch Panels

Typically a passive patch-in-patch-out loss is ~1 dB (0.5 dB per connection), although this is heavily dependent on the type of connection or interface.

3 Optical Data Transmission

3.1 Laser Modulation

Fiber communication systems typically employ some form of digital communication technique that requires the laser to be switched *ON* to transmit a digital *1* and switched *OFF* to transmit a digital *0*. To transmit a digital *0* the laser is biased slightly above the threshold where the optical output power will be at its lowest.

Conversely, to generate a digital *1*, a current pulse is applied to the laser so that its optical output power will be at its highest specified level.

The amplitude of the signal can be adjusted so as not to exceed the maximum current rating of the laser but high enough so that the difference in optical power representing a *1* and that representing a *0* is easily distinguished by the optical receiver. The decision level of the receiver is usually set halfway between the minimum and maximum transmitted power. The ratio between the high power state (*1*) and the low power state (*0*) is called the ***extinction ratio***. Maximizing the extinction ratio while not over driving the laser transmitter, results in better noise immunity and better sensitivity at the receiver.

SMPTE ST 297 defines a minimum extinction ratio of 5:1 with 10:1 preferred for an optical transmitter.

3.2 Encoding/ Decoding

In order to transfer data over a high-speed serial interface, data is encoded prior to transmission and decoded upon reception. The encoding process ensures that an average DC balance of ‘1’s and ‘0’s are present in the serial stream in addition to ensuring that there are sufficient transitions to enable clock and data recovery circuits in the receiver to synchronize and successfully recover the data.

The encoding scheme used to encode a datacom signal is very different to the encoding scheme used to encode SDI signals and have different signaling properties and stress conditions than SDI signals.

Typically, datacom signals use a 8b/10b (8 bit/ 10 bit) encoding or a 64b/66b encoding with scrambling while SDI signals use a self synchronizing scrambler followed by NRZI (Non return to zero, inverted) encoding.

3.3 Pathological Patterns

This SDI coding scheme is capable of generating output sequences with DC imbalance and low transition density creating a pathological signaling condition containing a series of bits of fixed polarity.

These pathological patterns can cause errors when transported over optical systems that employ “off the shelf” optical components. Optical components designed for datacom applications for example are generally designed to use an AC-balanced signal with a duty cycle of approximately 50%. This allows the optical transceiver to properly modulate the laser control loop (transmit side) and lock (PLL circuitry) in its receiver.

Because the SDI coding scheme does not provide an AC-balanced signal, optical components specifically designed for use with the pathological patterns are required for error-free transport of SDI signals.

4 Optical System Architecture

4.1 Optical Fiber

The anatomy of an optical fiber can be seen in Figure 9 and is described below.

Optical fiber typically consists of a doped silica core surrounded by a cladding material with a lower index of refraction. Light is kept in the core by total internal reflection. This causes the fiber to act as a waveguide. The cladding is covered in a silicone or acrylate coating and a hard plastic buffer coating to protect the core and cladding.

Kevlar strengthening fibers are added to give the fiber pulling strength, and finally an outer protective jacket typically made of PVC is included.

The majority of the optical energy is contained within the core of the fiber. The core/cladding geometries and compositions define the optical performance.

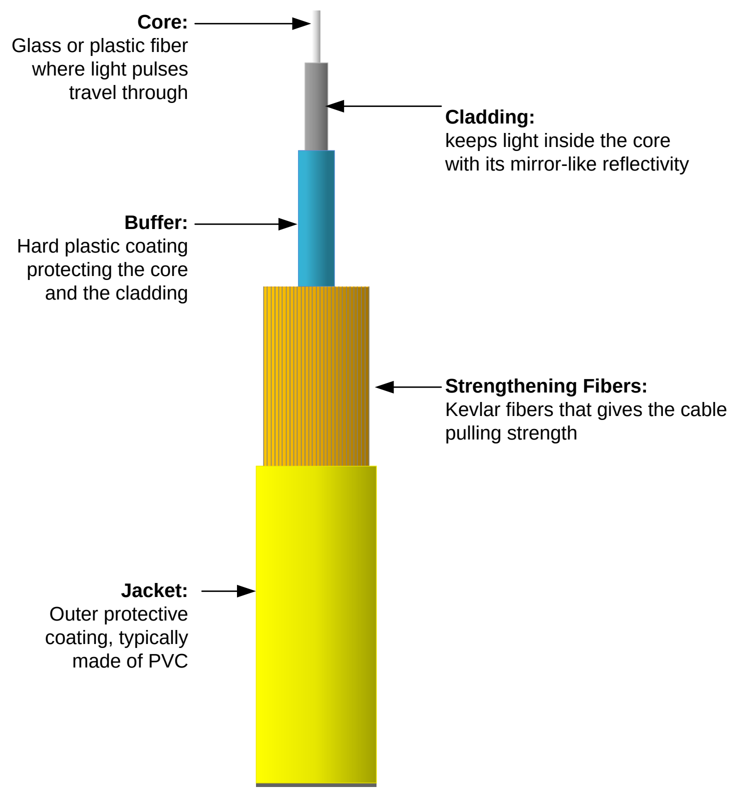
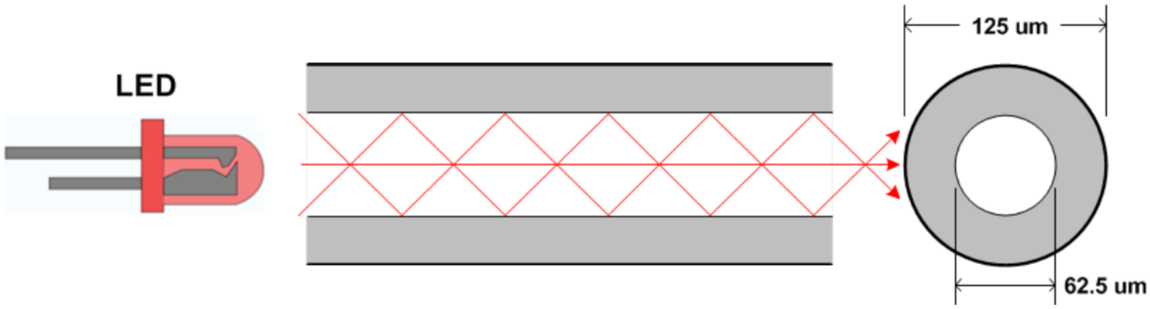


Figure 9 – The anatomy of an optical fiber

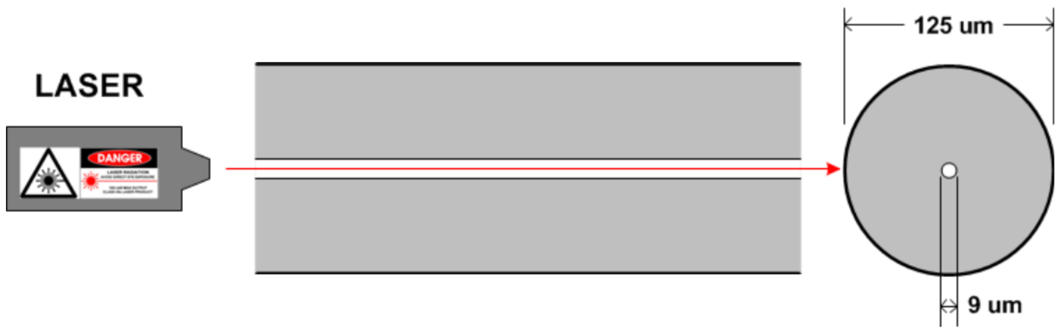
4.1.1 Fiber types

There are different types of optical fiber. Fibers which support many propagation paths or transverse guided modes are called multi-mode fibers (MMF), while those which can only support a single mode are called single-mode fibers (SMF).

Multi-mode fibers generally have a large 50 um~62.5 um core diameter and support multiple modes of light propagation; support a wide light source (LED / VCSEL); have lower bandwidth, higher dispersion / power loss and are used for short-distance communication links.



Single mode fibers have a small 9 um core diameter and limit the light propagation to a single path; they support a narrow light source (laser); have higher bandwidth; lower dispersion and power loss and are used for longer communication links as well as for optical multiplexing solutions.



Typically, multi-mode fibers have an orange outer jacket and single mode fibers have a yellow outer jacket so that it is easy to identify the specific fiber type in any installation.

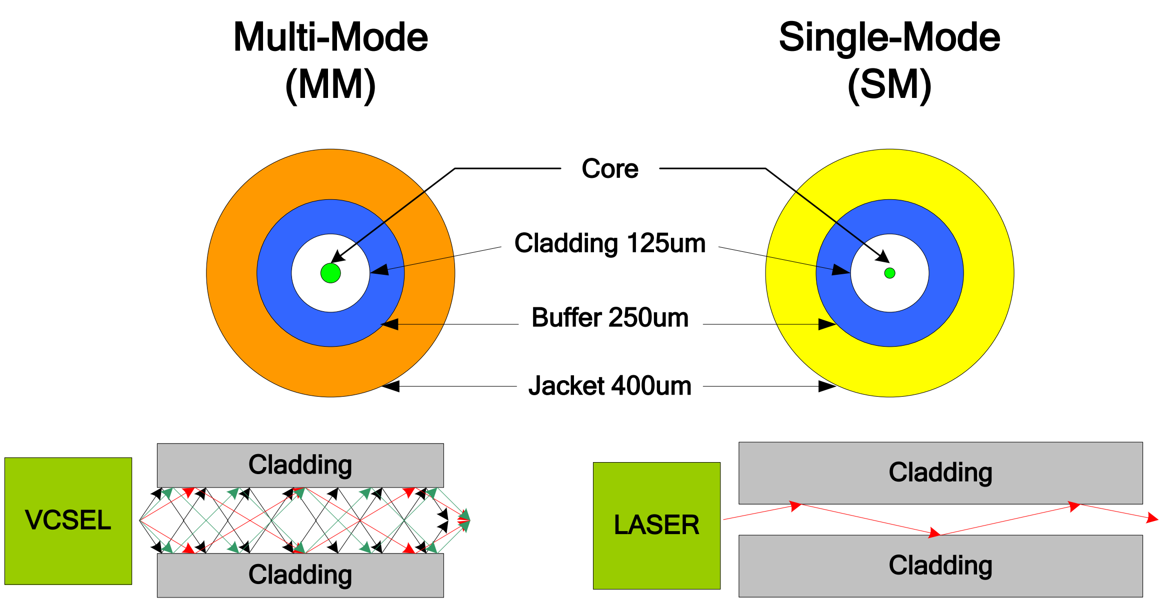


Figure 10 – A comparison of a single mode and a multimode fiber.

SMPTE ST 297 specifies the use of single-mode fiber (compliant with ITU-T Rec. G.652), for high-power / long-haul and medium-power / medium-haul applications. It also specifies either single-mode or multimode fiber (compliant with ANSI/EIA/TIA-492AAAA-A (62.5/125 micron graded-index [GI] fiber or ITU-T G.651 (50/125 micron graded-index [GI] fiber), for low-power / short-haul link applications.

SMPTE ST 297 also notes that point-to-point circuits can be constructed from one or multiple serially interconnected sections of the selected type of optical fiber in cables, jumpers, and/or patch cords. Mixing fiber types in the multiple sections of a point-to-point circuit although physically possible, is technically unacceptable and would not be in compliance with SMPTE ST 297.

4.1.2 Signal Degradation in Fiber

As the optical signal propagates within the fiber, signal degradation will occur. The two types of degradation that can occur in an optical path are attenuation and dispersion.

4.1.2.1 Attenuation

Attenuation is the loss of optical power as the signal travels through the fiber. Attenuation is a result of 2 main factors which are both wavelength dependant; absorption and scattering. There is an intrinsic material absorption from the silica fiber and impurities — mainly water — which cause severe attenuations at certain wavelengths. Attenuation due to scattering is a function of wavelength, and decreases as the wavelength increases.

Figure 11 shows the attenuation in optical fiber as a result of both absorption and scattering.

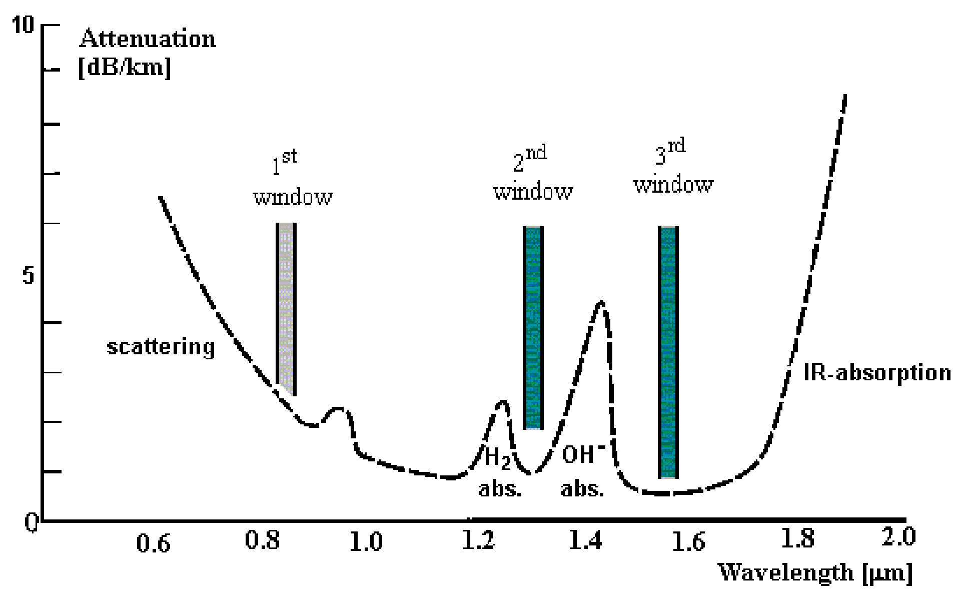


Figure 11 – Fiber attenuation over wavelength

Optical systems usually employ wavelengths between the absorption peaks and for longer link distances employ longer wavelengths for lower loss. Wavelengths of 850 nm, 1310 nm and 1550 nm are commonly used as they lie in the valleys of the absorption curve.

SMPTE ST 297 specifies a maximum attenuation of 0.35 dB per kilometer at 1310 nm, and 0.25 dB per kilometer at 1550 nm for single mode fiber used in compliant optical SDI systems. It also specifies a maximum attenuation of 1.5 dB per kilometer at 1310 nm and 3.75 dB per kilometer at 850 nm for multimode fiber used in compliant optical SDI systems.

4.1.2.2 Dispersion

Dispersion also contributes to the signal degradation within the fiber. Dispersion can be thought of as the spreading of the signal pulses as they travel through the fiber. There are two main forms of dispersion — modal dispersion and chromatic dispersion.

Modal Dispersion: In a fiber with a large core such as a multimode fiber, many modes can propagate through the fiber. These modes propagate at different speeds and arrive at the end of the fiber at different times. This distorts the shape of the signal as depicted in Figure 12.

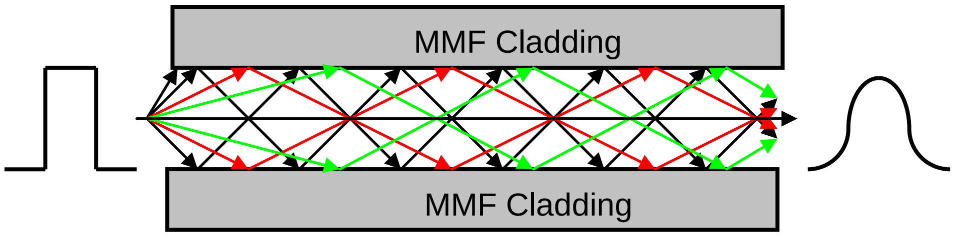


Figure 12 – **Intermodal Dispersion**

Some multimode fibers contain a core with a graded index of refraction to help reduce the effects of modal dispersion, but it cannot be eliminated. Modal dispersion is the limiting factor which determines the distance a signal can travel in a MMF.

SMPTE ST 297 specifies the use of graded-index [GI] multimode fiber in compliant optical SDI systems.

Chromatic Dispersion: The velocity of light through a SMF depends on its wavelength. For high data-rate and/or long distance systems, single mode (SM) fiber is used with a more coherent laser as the light source. However, all lasers have finite spectral widths and they transmit a pulse of light comprising multiple wavelengths.

Pulse spreading occurs due to the propagation of these different wavelengths through the fiber. Shorter wavelength light pulses arrive at a different time to the longer wavelength light pulses and eventually adjacent pulses overlap. This is depicted in Figure 13.

This effect is known as chromatic dispersion which is measured in psec/nm-km. and chromatic dispersion is therefore the limiting factor in determining the distance a signal can travel in a SMF.

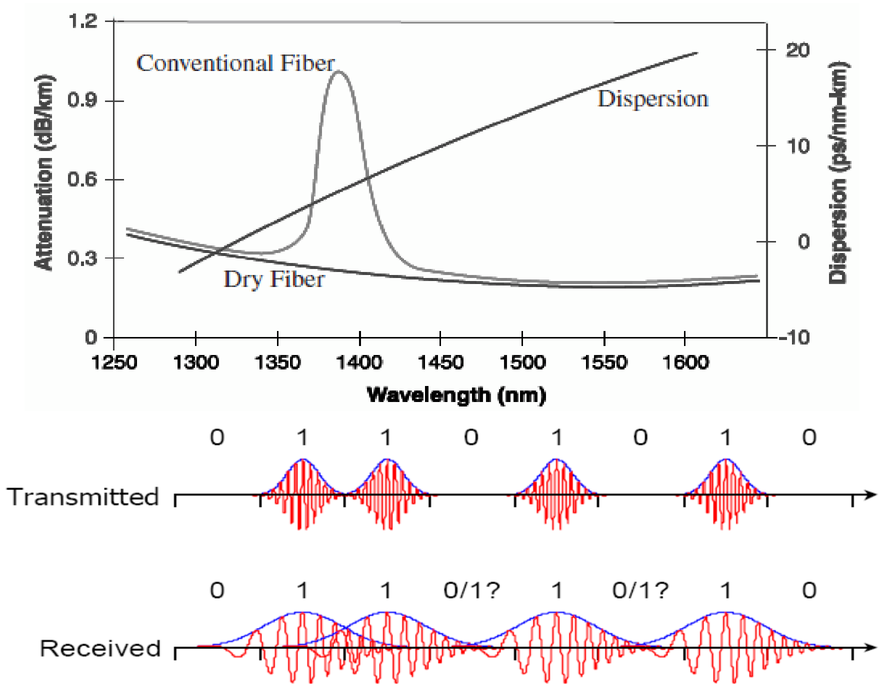


Figure 13 – Chromatic Dispersion

DFB lasers have a narrower output spectrum than FP lasers, thus they yield less dispersion and can achieve longer distances.

4.2 Fiber Connectors

Since fiber optic technology was first introduced, a number of different connectors and connector styles have entered the market. Each new design offers better performance (less light loss, or less back reflection), easier termination or lower cost.

SMPTE ST 297 recommends the preferred connector type as LC/PC as per IEC 61754-20-1, but notes other application-specific connector types such as SC, ST, FC, MU, etc. can optionally be used in accordance with the specific demands of the application.

In a connector, only the light that is coupled into the receiving fiber's core will propagate, so all the rest of the light becomes the connector loss. In an ideal connector, the light would couple perfectly into the fiber core of the receiving fiber with no loss or back reflection. Of course, there are no ideal connectors, but loss is minimized when two fiber cores are identical and perfectly aligned, the connectors or splices are properly finished and no dirt is present.

Gaps in the connectors (between the transmitting fiber core and the receiving fiber core) cause two main problems; insertion loss and back reflection (optical return loss). Light that is not coupled into the receiving fiber core is insertion loss, and the larger the gap, the larger the insertion loss for identical fiber types.

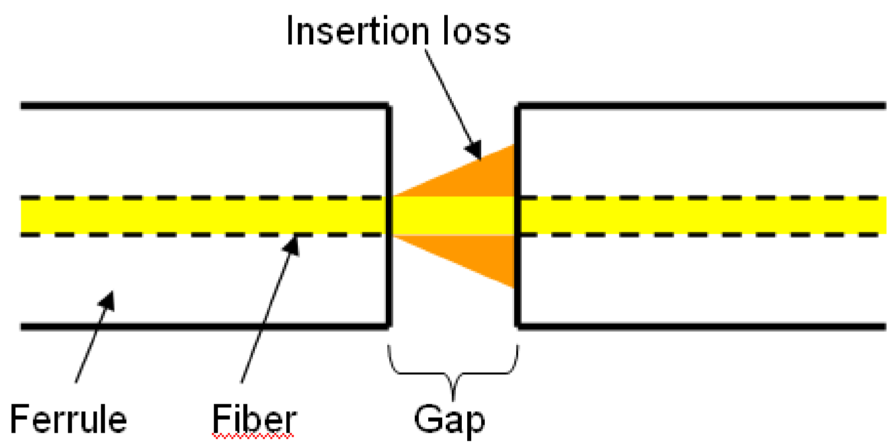


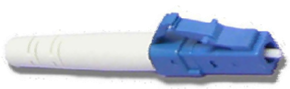
Figure 14 – Insertion Loss in coupling 2 fibers

The air gap also causes back reflection commonly referred to as optical return loss (ORL). This reflection occurs when light encounters a change in the refractive index — this is known as Fresnel reflection. This reflection can interfere with transmitter performance. Optical isolators are used to minimize the effects of ORL. See Section 2.1.3 for more on optical isolators.

4.2.1 Fiber Connector Types

Common fiber connectors in use today are illustrated in Table 2.

Table 2 – Common fiber connectors

Connectors			Description
	FC	Screw On	The FC connector has been one of the most popular single mode connectors for many years. It is now being replaced by SC and LC connectors
	ST	Twist Lock/ BNC type	ST is the most popular connector for multimode networks. It has a bayonet mount and a long cylindrical ferrule to hold the fiber.
	SC	Snap-in	SC is a snap-in connector that is widely used in single mode systems for its excellent performance. It is also available in a duplex configuration.
	LC	Snap-in	LC is a new small form factor connector that is half the size of the ST. It has good performance and is highly favored for single mode applications. The LC connector is the standard connector for SFP optical modules and is very popular within optical SDI systems
	SMPTE 304	Snap-in	Hybrid connector commonly used in many broadcast applications containing 2 fibers, 2 signal, and 2 power connections.

4.2.2 Ferrule

The most important part of the connector is the ferrule. The ferrule is the rigid part of the connector that confines and protects the fiber. The ferrule tip is typically made of ceramic or metal and can have many different shapes or finishes usually referred to as polishes. Early connectors did not have keyed ferrules which allowed the ferrules to rotate in mating adapters. To prevent grinding scratches due to the ferrule rotation, there was always an air gap between the connectors.

To reduce both the insertion loss and the back reflection that resulted from an air gap, connectors with keyed ferrules were designed to contact tightly, in what are called physical contact (PC) connectors. While air gap connectors usually had losses of 1.0 dB or more and return loss of 15 dB, PC single mode connectors provide typical losses of 0.5 dB and a return loss of approximately 28 dB.

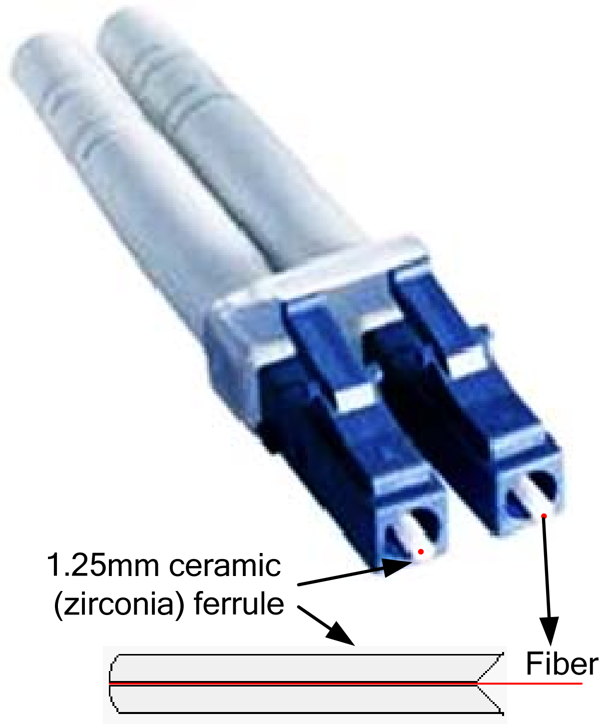


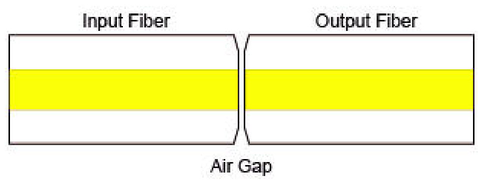
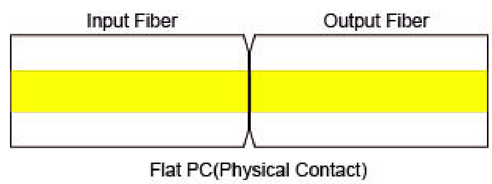
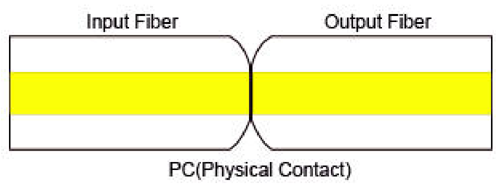
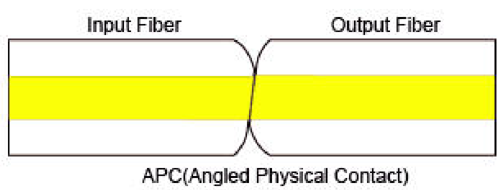
Figure 15 – LC Duplex – fiber ferrule

Making the connector ferrules convex produces an even better connection. The convex ferrule guarantees the fiber cores are in contact. Losses under 0.5 dB and a return loss of 35 dB or better can be achieved.

Further improvements to the polishing process (Super Physical Contact (SPC), Ultra Physical Contact (UPC)), produce insertion losses of 0.3 dB and return losses > 45 dB.

The most effective solution for systems extremely sensitive to reflections is to angle the end of the ferrule by 8 degrees to create an APC or angled PC connector. Any reflected light is at too large an angle to propagate along the fiber core so leaks into and is absorbed by the cladding. Table 3 shows examples of different ferrule polishes.

Table 3 – Types of connector mating

Connector		Typical Insertion Loss	Typical ORL
Air Gap	 Lack of keyed ferrules allows rotation in mating adapters. Air gap needed to prevent grinding scratches on fiber ends	1.0 dB	-15 dB
Flat Physical Contact (Flat PC)	 FC and ST have keyed ferrules, the connectors are designed to contact tightly	.5 dB	-28 dB
Physical Contact (PC / SPC / UPC)	 Convex ferrule produces a better connection and contact of the fiber cores	.3 dB	-40 dB
Angled Physical Contact (APC)	 8 degrees angle cut ferrule. Angled reflected light is absorbed in the cladding improving return loss	.25 dB	-60 dB

There is some compatibility between the polished ferrules. PC and Flat PC polishes are compatible and can be mixed and matched. However, ferrules with APC polishes can only be connected to other ferrules with APC polishes. They cannot be mixed with other polishes.

SMPTE ST 297 recommends a PC polish although SPC (Super Physical Contact), UPC (Ultra Physical Contact), and APC can be used but must be clearly labeled according to SMPTE ST 297 labeling requirements.

4.3 *Handling*

Optical fibers generally enable stable transmission of signals when the fiber is in place. However, the stability and quality of the signal can be affected by the condition and handling of the fiber.

4.3.1 Inspection and Cleaning

Clean fiber optic connectors and components are a requirement for quality connections between fiber optic equipment. One of the most basic and important procedures for the maintenance of fiber optic systems is to clean the fiber optic equipment end faces.

Any contamination in the fiber connection can cause failure of the component or failure of the whole system. Even microscopic dust particles can cause a variety of problems for optical connections. A particle that partially or completely blocks the core generates strong back reflections, which can cause instability in the laser system. Dust particles trapped between two fiber faces can scratch the glass surfaces. Even if a particle is only situated on the cladding or the edge of the end face, it can cause an air gap or misalignment between the fiber cores which significantly degrades the optical signal.

Dust might not be visible to the naked eye, but it is still present in the air and can deposit onto the connector. In addition to dust, other types of contamination must also be cleaned off the end face. Such materials include:

- Oils, frequently from human hands
- Film residues, condensed from vapors in the air
- Powdery coatings, left after water or other solvents evaporate away

These contaminants can be more difficult to remove than dust particles and can also cause damage to equipment if not removed.

It is recommended that the fiber connector, the component or bulkhead be inspected with a fiberscope prior to making a connection and cleaned if required.

Some examples of typical defects are shown in Figure 16.

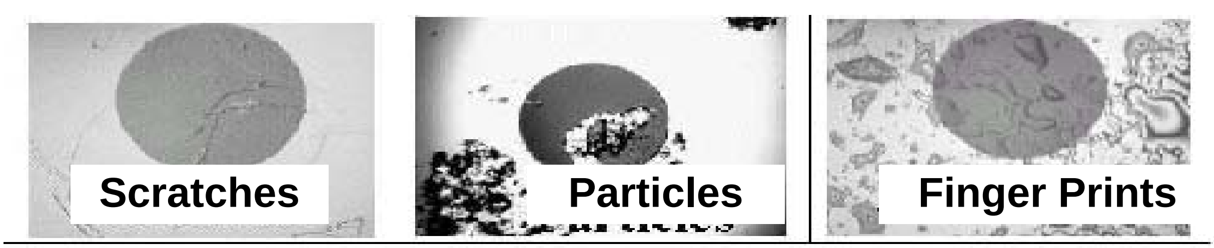


Figure 16 – Typical inspection defects

Industry standard IPC-8497-1 sets guidelines and inspection criteria for both multimode and single mode fiber connector inspection. This document provides a useful reference when determining an acceptable level of contamination or damage..

4.3.2 Fiber Optic Cleaning Methods

Fiber optic cleaning kits on the market can be divided to four types based on the cleaning method.

- Dry cleaning: Optic cleaning without the use of any solvent.
- Wet cleaning: Optic cleaning with a solvent such as isopropyl alcohol (IPA).
- Non-Abrasive cleaning: Cleaning without abrasive material touching the fiber optic connector end face. Examples are air dusters or pressured solvent jet used in automated in-situ connector cleaners.
- Abrasive cleaning: The popular lint free wipes, reel based Cletop fiber connector cleaners and optic cleaning swabs such as the Cletop sticks are all abrasive cleaning types.

Although opinion varies greatly when it comes to cleaning, it is recommended that air dusters and solvent sprays not be used unless they are propellant free as the propellants can both damage and leave residue. Regardless of the method chosen, it is important to realize that no cleaning method is 100% effective.   After each cleaning step, further inspection is recommended.

4.4 Splicing

Splicing is the term used to describe the permanent connection of one fiber optic cable to another fiber optic cable. Although splicing is sometimes necessary for repairs in the field or connecting pigtails etc., it is not a practice that is commonly done.

At first glance, splicing two fiber optic cables together is analogous to connecting two wires; however, the requirements for a fiber-optic connection and a wire connection are very different.

Two copper connectors can be joined by solder or by connectors that have been crimped or soldered to the wires. The purpose is to create an intimate contact between the mated halves in order to have a low resistance path across a junction.

Connecting two fiber optic cables on the other hand, requires precise alignment of the mated fiber cores in a single-mode fiber optic cable. This is required to ensure that all of the light is coupled from one fiber optic cable across a junction to the other fiber optic cable without causing back-reflections.

There are two principal types of splices: fusion and mechanical.

Fusion splices: In fusion splicing a machine is used to precisely align the two fiber ends then the glass ends are "fused" or "welded" together using heat or electric arc. This splicing method uses sophisticated computer controlled alignment equipment to produce a continuous connection between the fibers achieving losses as low: 0.05 dB.

Mechanical splices: Mechanical splices are easily applied in the field, require little tooling and offer losses of about 0.2 dB.

5 Fiber Optic Multiplexing

The links discussed thus far have been single point to point links with a single channel carrying one data stream per fiber. This is a simple system that requires no filtering at the receiver and little control over the transmitter wavelength. To send another signal, one could add another fiber link, but this is not always desirable. The optical fiber has a large bandwidth and is capable of carrying multiple signals. To accomplish this multiplexing is required. Time division and wavelength division multiplexing are the two most commonly used.

5.1 Time Division Multiplexing (TDM)

The TDM multiplex is controlled in the electrical domain and is synchronous. A typical TDM system is shown in Figure 17.

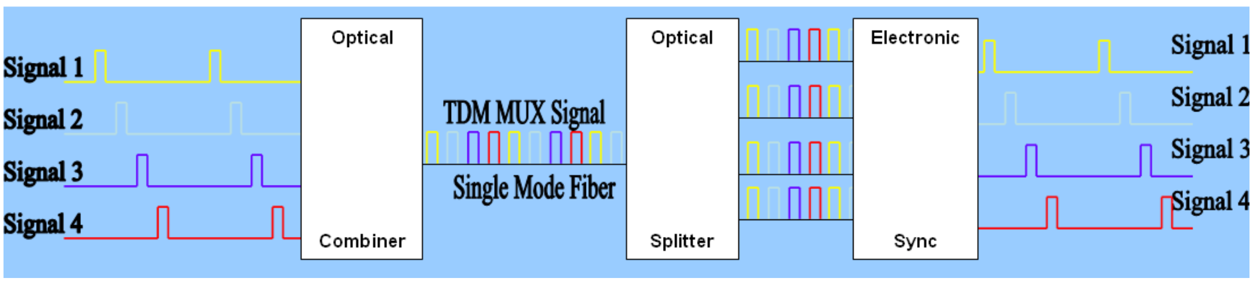


Figure 17 – TDM system

The optical requirements for a TDM system are inexpensive, but there are disadvantages. There is a high cost of synchronization; a limited number of signals can be used based on the maximum link rate, and the distance is limited by the dispersion within the fiber.

5.2 Wavelength Division Multiplexing (WDM)

In wavelength division multiplexing (WDM) multiple DFB lasers are tuned to specific wavelengths which are grouped together with optical filters (Optical MUX) and travel independently along the fiber. At the end of the fiber filters are used to separate (Optical Demux) the individual wavelengths. A typical WDM system is depicted in Figure 18.

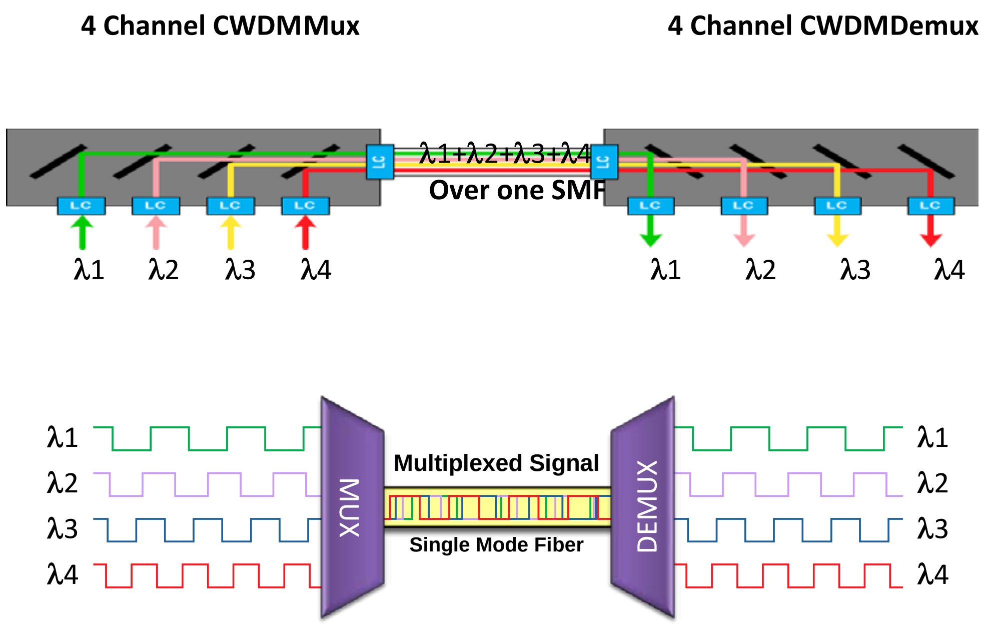


Figure 18 – WDM system

The Optical mux and optical demux consist of a Series of passive optical filters made with prisms, thin film filters, dichroic filters or interference filters.

Each filter reflects a single wavelength of light and pass all others almost transparently (Average loss/filter ≅ .5 dB)

4 channel CWDM → Total Mux+Demux loss/channel ≅ 2 dB

8 channel CWDM → Total Mux+Demux loss/channel ≅ 4 dB

16 channel CWDM → Total Mux+Demux loss/channel ≅ 7 dB

It is important to note that each wavelength can operate at an independent bit rate and will not interfere with any of the other signals. This allows multiple different image formats and signal types, such as AES, MADI, DVB-ASI, 3G/HD/SD SDI or Ethernet to be carried simultaneously on a single fiber.

Course Wavelength Division Multiplexing (CWDM) uses wavelengths separated by 20 nm beginning at 1271 nm to 1611 nm as defined in ITU-T G.694.2 Spectral grids for WDM applications: CWDM wavelength grid.

There are a total of 18 wavelengths available but 2 wavelengths (1390 nm and 1410 nm as specified in ITU-T G.652a/b) are not typically used as they overlap the water absorption peak.

To use all 18 wavelengths, a special "low water peak fiber" ITU-T G.652c/d is required. Figure 19 depicts the CWDM bands.

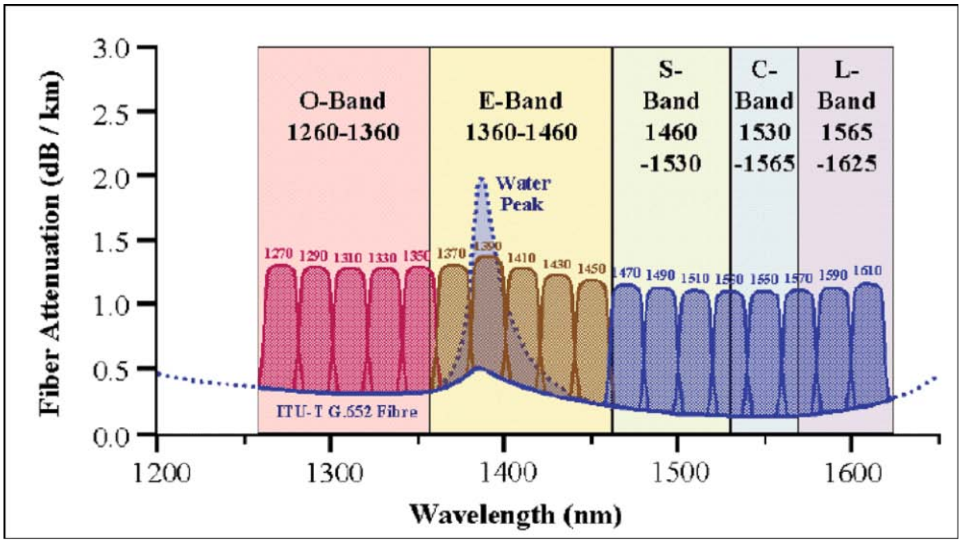


Figure 19 – CWDM wavelength bands

In a Dense Wavelength Division Multiplexing (DWDM) system, wavelengths are separated by 0.2 nm to 3.2 nm from 1550 nm to 1610 nm as defined in ITU-T G.694.1 Spectral grids for WDM applications: DWDM frequency grid.

This allows up to 160 wavelengths per fiber. The narrow spacing requires high stability lasers and more complex filters to MUX and DEMUX the signals leading to a much higher system implementation cost. This generally makes DWDM too expensive to implement for point-to-point and campus applications.

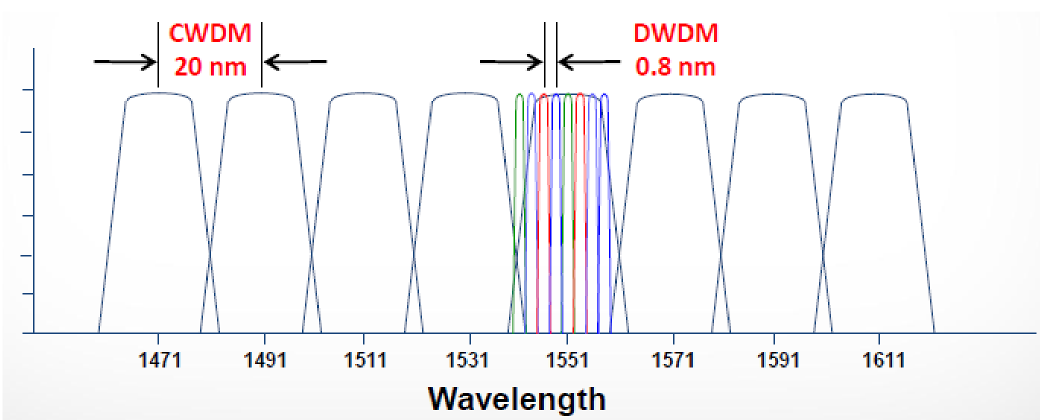


Figure 20 – DWDM wavelength bands and spacing

Typically CWDM is used for regional or metro installations with link distances less than 60 km, while DWDM is generally used for long haul applications.

6 SFP Modules

The small form-factor pluggable (SFP) module combines transmitter and/or receiver functions in a compact, flexible and cost effective package. The SFP is a self contained, hot pluggable, electrical to optical or optical to electrical converter.

Figure 21 – SFP module

Due to its compact size and flexibility, the SFP form factor has become the most common module used in optical SDI transport systems.

The SFP modules can be configured in many variants. The most popular products used in optical SDI transport are:

- Dual channel transmitters
- Dual channel receivers
- Single channel transmitters
- Single channel receivers
- Transceivers

The SFP houses the Transmit Optical Sub-Assembly (TOSA); Receive Optical Sub-Assembly (ROSA), and all the components required to make the electrical to optical or optical to electrical conversion. Further information on transmitter and receiver design can be found in Annex A and B of this standard. The key components that make up an SFP can be seen in Figure 22.

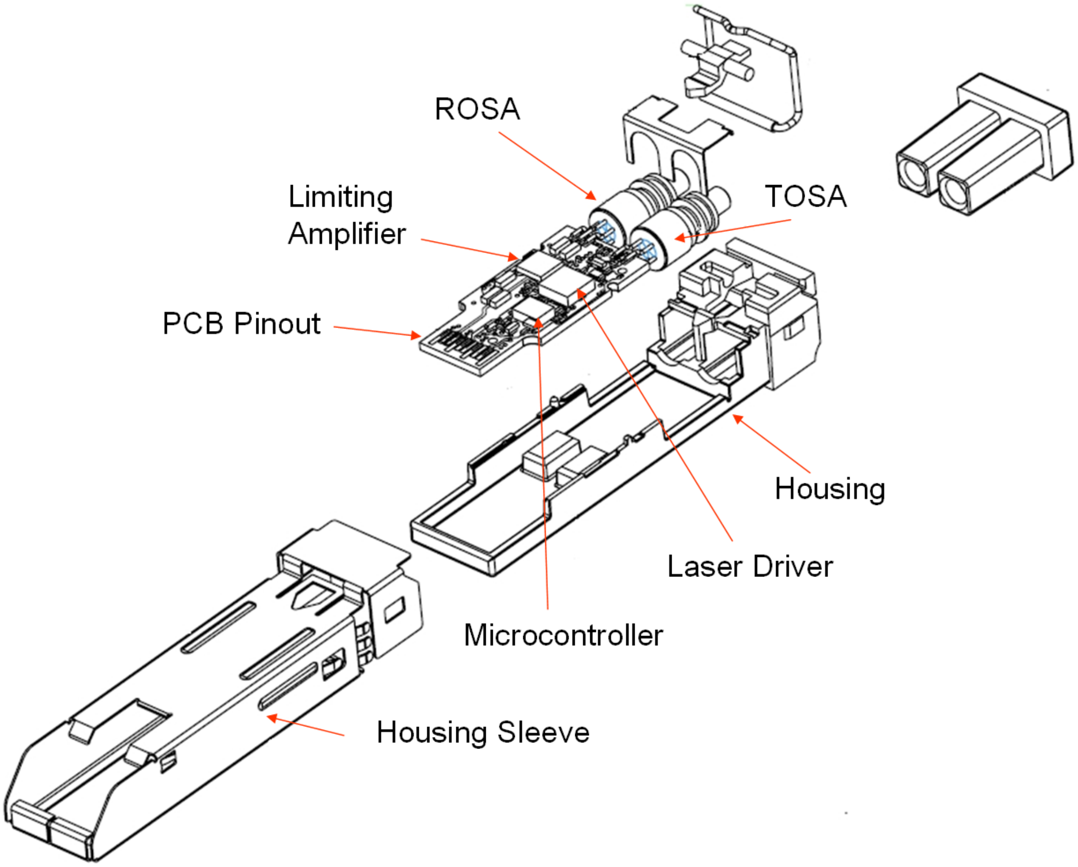


Figure 22 – Make up of a typical SFP Transceiver

The SFP transceiver has been popular in the datacom, telecom and storage markets and has been specified by a Multi-Source Agreement (MSA) between competing manufactures to ensure interoperability. The MSA (INF-8074i) specifies key electromechanical aspects of the module such as mechanical dimensions, electrical connector pin assignment, EEPROM content, power supply and management interface. The MSA is a transceiver specification that was derived by and for the datacom, telecom and storage markets, and although optical SDI SFPs share much of the MSA, there are some major differences.

6.1 Pin Assignment

The MSA defines a specific transceiver based pin-out for a SFP module as all MSA modules are transceiver devices featuring one transmit channel and one receive channel.

SFP modules used in optical SDI applications are typically dual channel transmitters, dual channel receivers, single channel transmitters or single channel receivers. Some broadcast video applications require transceiver functionality but this is not common. In order to accommodate all of the variants required to meet video specific applications, a new de-facto optical SDI SFP pin-out has been created to enable a single board design to accept any of the variants. This pin out is often referred to as the video SFP interface (VSFP) or the Non-MSA pin-out.

The VSFP pin-out varies from the MSA defined pin out as shown in Figure 23.

MSA Pin Assignment

INF-8074i Transceiver Pinout			
20	VeeT	VeeT	1
19	TD-	TxFault	2
18	TD+	TxDisable	3
17	VeeT	SDA	4
16	VccT	SCL	5
15	VccR	ModDef0	6
14	VeeR	RateSelect	7
13	RD+	LOS	8
12	RD-	VeeR	9
11	VeeR	VeeR	10

Video SFP Pin Assignment

Video Transceiver Pinout			
20	TxDisable	VeeT	1
19	TD-	TxFault	2
18	TD+	NC	3
17	VeeT	VeeT	4
16	VccT	SCL	5
15	VccR	SDA	6
14	VeeR	VeeR	7
13	RD+	LOS	8
12	RD-	NC	9
11	VeeR	NC	10

Video Dual Receiver Pinout			
20	NC	Vee	1
19	NC	RD2-	2
18	NC	RD2+	3
17	Vee	Vee	4
16	VccRx2	SCL	5
15	VccRX1	SDA	6
14	Vee	Vee	7
13	RD1+	NC	8
12	RD1-	NC	9
11	Vee	NC	10

Video Dual Transmitter Pinout			
20	Tx1Disable	Vee	1
19	TD1-	NC	2
18	TD1+	NC	3
17	Vee	Vee	4
16	VccTx1	SCL	5
15	VccTx2	SDA	6
14	Vee	Vee	7
13	NC	TD2+	8
12	NC	TD2-	9
11	Vee	TX2Disable	10

Figure 23 – Pin Assignments

6.2 EEPROM

The SFP MSA (INF-8074i) also defines a 256-byte memory map in EEPROM describing the transceivers capabilities, product identification, manufacturer, and other information that is accessible over an I2C interface.

As with the pin assignment, there are differences in the descriptor fields used for a dual channel receiver or dual channel transmitter Video SFP, as these product types do not exist in the MSA. The Video SFP datasheet usually specifies the values for the various registers in the EEPROM.

6.3 Digital Diagnostic Monitoring

Both Video SFPs and MSA compliant SFPs support digital diagnostic monitoring functions according to the standard SFF-8472. This gives the end user the ability to monitor real time parameters such as optical power, temperature and laser bias current. This function is also available through the I2C interface.

6.4 SFP Labeling

SMPTE ST 297 specifies labeling to indicate some key elements of the module. The specific codes and details of the label are specified in SMPTE ST 297. The key elements include:

- the application (low power, medium power, high power)
- the polish of the connector,
- the payload type they support,
- the wavelength supported.

7 Link Budgeting

When designing an optical fiber link to cover a known distance, there are two factors that will decide whether a particular transmit-receive pair will be adequate to successfully transport data while meeting or exceeding the minimum BER requirements of SMPTE ST 297.

These factors are the *power budget* and the *dispersion tolerance* of the Tx/Rx pair.

7.1 Power budget

The power budget is composed of two principal elements:

Transmit power: This is the guaranteed end of life (EOL) average output optical power of the transmit laser, normally expressed in mW or dBm. Start of Life (SOL) values will typically be larger, allowing for some relaxation in the output power as the device ages.

Receive sensitivity: This is the guaranteed end of life (EOL) power level at which satisfactory error performance can be achieved with a known data pattern. Sensitivity levels for pathological signals will typically be poorer than for PRBS signals (Pseudo Random Bit Sequence).

When determining the loss-limited reach of the system, subtracting the receive sensitivity from the transmit power will provide the power budget (sometimes referred to as "link budget").

Table 4 – Power budget calculation

TX: Optical Output Power	-7dBm to +7dBm
Rx: Optical Sensitivity	-11dBm to -32dBm
Power Budget	**Tx - Rx**

An estimate of the loss-limited reach can be attained from dividing the power budget by an estimate of the fiber loss at the wavelength of interest. For a 1310 nm-centered FP source, a typical SM fiber optic cable loss can be estimated at 0.35 dB/km and for 1550 nm-centered DPB source a typical SM fiber optical cable loss can be estimated at 0.25 dB/km

It is also important to consider the number of connection points, splice points, and passive optical devices, such as optical multiplexers and splitters which will introduce power loss into the system. Loss at a connector can be estimated at 0.5 dB, while devices such as MUXs can contribute anywhere from 1 dB to 12 dB of loss depending on the wavelength and the device itself. It is also prudent in these calculations to account for system margin before calculating the loss-limited reach to account for other system issues such as fiber loss due to bending, source wavelength drift, etc.

Table 5 – Typical passive device power loss

Single Mode Fiber Loss	
FP (1310nm)	0.35dB/km
DFB (1550nm)	0.25dB/km
Insertion Loss	
Connectors	0.5dB
Splices	0.2dB
Patch Panels	1dB
Passive Device Attenuation	
WDM	2dB
CWDM 16	7dB
DWDM 32	12dB
Splitter 80%	2dB
Splitter 20%	9dB

A more accurate estimate of system reach can be achieved by measuring the fiber loss at the desired wavelength prior to deploying the link.

Dispersion: As discussed in Section 4.1.2.2, Chromatic Dispersion (CD) is the change in mode effective index, and hence energy propagation velocity, with respect to wavelength. That is, every wavelength of light propagating along an optical fiber will experience a different propagation velocity. The presence of dispersion leads to an "erosion" of the unit interval as the energy from neighbouring pulses spread into the current bit period. Similarly, energy from the current bit period is redistributed into the bits before and after.

The dispersion tolerance of the Tx/Rx pair is composed of several elements:

Source line width: Source line width is very dependant on the laser technology used in the transmitter. Fabry-Perot sources (FP) have a very broad spectral line width on the order of several nanometers. Distributed Feed Back (DFB) lasers have a narrow line width on the order of only tenths of a nanometer. The broader the line width of the laser, the more susceptible the data transmission will be to dispersion.

Source wavelength and fiber type: All the various fiber types in existence have a wavelength point at which the dispersion crosses through zero. Depending on the type of fiber and the wavelength of the transmitter, the data is subjected to a certain amount of dispersion as it propagates through the fiber. The most common single-mode fiber type is SMF28 which has a zero-dispersion wavelength centered at 1310 nm.

Receive tolerance to inter-symbol interference (ISI): Typically, receivers can tolerate a finite amount of interference from the leading/trailing bits into the current bit period. A typical ISI design value is 49% of the unit interval which results in a 2 dB reduction in receiver sensitivity.

Data rate: Since dispersion manifests itself as a delay in the signal between the start and end of the pulse, it becomes more of a problem at higher data rates where the unit interval is correspondingly shorter.

7.2 Calculating Link Distance

For a full design consideration, it is necessary to determine whether a Tx/Rx pair will be power limited or dispersion limited. Calculating a reach for both power **and** dispersion will highlight the fiber length at which the system becomes limited for one of these phenomena.

By way of example, the following optical network is considered for calculating the link distance.

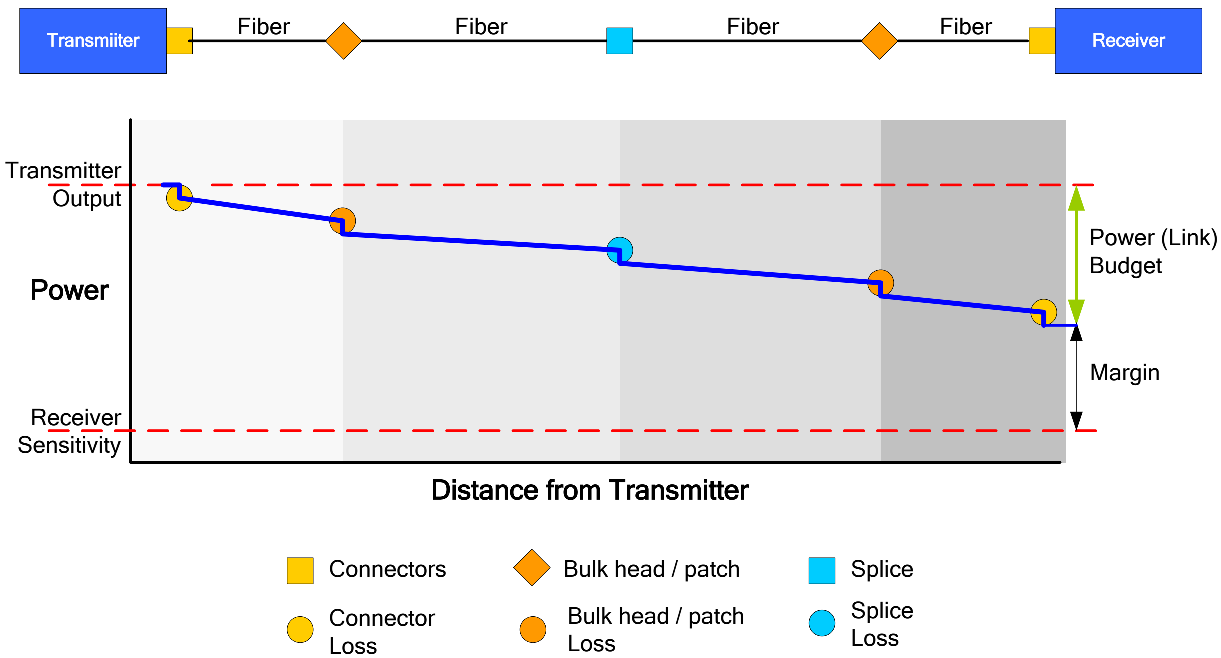


Figure 24 – Signal loss in a typical Optical SDI installation

7.2.1 Single Mode link distance calculation

For this example, the following basic assumptions apply:

The SM fiber loss is fixed at a uniform, worst case 0.35 dB/km
1310 nm FP transmitter – minimum output power → -5 dBm, spectral width 4 nm
PIN Receiver – minimum sensitivity (pathological) of -18 dBm
2 connectors with .5 dB loss / connector
2 patch losses with 1 dB loss / patch
1 splice loss with 0.3 dB loss / splice
3 dB system margin added

The worst case, EOL power budget for this example would therefore be:

Transmitter power	- 5 dBm
Receiver Sensitivity	- (-18 dBm)
Connector loss (2x .5)	- 1
Patch loss (2 x 1dB)	- 2
Splice loss (0.3dB)	- 0.3
System margin	- 3
EOL power budget	6.7 dB

The *estimated* reach is 6.7/0.35 = **19.14 km**

Dispersion: For a SMF having a zero-dispersion wavelength centered at 1302 nm and a laser optical wavelength of 1310 nm +/-40 nm (from SMPTE ST 297), the dispersion coefficient can be calculated using the zero-dispersion slope parameter which can be obtained from the fiber data sheet..

Note: Zero-dispersion wavelength and zero-dispersion slope parameters are provided in the optical fiber data sheet.

For this example it is assumed that a zero-dispersion slope of 0.092 ps/(nm•km) is specified.

Calculating dispersion at 1270 nm (1310 nm -40 nm from ST 297) = -2.94 ps/nm.km

Calculating dispersion at 1350 nm (1310 nm +40 nm from ST 297) = 4.416 ps/nm.km

The dispersion limited link length is determined by the following equation:

$$L = \frac{0.491}{B.D.\Delta\lambda}$$

Where B is the bit rate, D is the dispersion (ps/nm.km) and $\Delta\lambda$ is the source line width (nm).

Choosing the worst case absolute dispersion of 4.416/nm.km, then for 1.5 Gb/s data, we get a dispersion-limited link length of **18.7 km**, and at 3.0 Gb/s, the length is reduced to **9.3k m**.

In this example it is clear that the link is dispersion limited at both 1.5 Gb/s and 3 Gb/s.

7.2.2 Multimode link distance calculation

In the case of Multimode fiber, the link distances are not often limited by overall power budget, but by modal dispersion (see Section 4.1.2.2).

Optical fiber manufactures specify the Effective Modal Bandwidth for multimode fiber at a given wavelength and this property is expressed in units of MHz •km.

There are several different multimode fiber types with differing core sizes and modal bandwidths. It is important to select the appropriate fiber for the required application.

Table 6 contains values for attenuation and minimum modal bandwidth for various fiber types. Actual values will be provided by the fiber manufacturer.

Table 6 – Multimode fiber parameters

Parameter	50/125 um			62.5/ 125 um
ISO/IEC 11801 Performance Category	OM2	OM3	OM4	OM1
Attenuation (dB/km) @ 850 nm @ 1300 nm	 <3.0 <1.0			 <3.5 <1.0
Effective Modal Bandwith (MHz •km) @ 850 nm @ 1300 nm	 >500 >500	 >1500 >500	 >3500 >500	 >200 >600

For this example, the following basic assumptions apply:

The worst case fiber loss for OM3 fiber at 850nm is 3 dB/km
850 nm FP transmitter – minimum output power → -5dBm
PIN Receiver – minimum sensitivity (pathological) of -18 dBm
2 connectors with .5 dB loss / connector
2 patch losses with 1 dB loss / patch
1 splice loss with 0.3 dB loss / splice
3 dB system margin added

The worst case, EOL power budget for this example would therefore be:

Transmitter power	- 5 dBm
Receiver Power	- (-18 dBm)
Connector loss (2x .5)	- 1
Patch loss (2 x 1 dB)	- 2
Splice loss (0.3 dB)	- 0.3
System margin	- 3
EOL power budget	6.7 dB

The *estimated* reach is 6.7 dB / 3 dB/km = **2.23 km**

Intermodal Dispersion: The formula for calculating the maximum link distance as a function of data rate is as follows:

Maximum distance = (Modal Bandwidth of Fiber) / (Datal Rate).

For OM3 MM fiber with a 50 um core, the effective modal bandwidth is 1500MHz•km at 850 nm.

For 1.5 Gb/s data, we get a dispersion-limited link length of **1 km**.

At 3.0 Gb/s, the length is reduced to ~**500 m**.

8 System / Network Evaluation

To ensure network integrity and robustness of an optical SDI link, it is critical to perform a careful and thorough evaluation of the optical components to be used. A thorough evaluation of the different optical components provides an understanding of the performance of the individual components and an indication of how much system margin that needs to be built into the system to ensure robustness of the link.

SMPTE ST 297 specifies the critical optical parameters for creating optical SDI links. Verification that the components under test comply with the SMPTE specifications over all operating conditions is recommended to ensure robust operation. The following sections outline some critical parameters and recommended tests to ensure robustness in an optical SDI link.

8.1 Receiver Testing

In evaluating a receiver, signals are sent using a reference transmitter to the receiver under test. The reference transmitter in the setup must be a high power optical transmitter so that the test bed can exercise the overload level of the receiver. Since the performance of a receiver can vary greatly with data rate, pattern, and temperature, it is important to test all data rates that are of interest with the pathological data pattern over the full operating temperature range. The reference transmitter must also be able to cope well with pathological signals.

The key performance parameters for an optical receiver include sensitivity and overload levels. These levels can be determined by measuring the bit error ratio as a function of input power.

A typical test bench for evaluating an optical receiver includes:

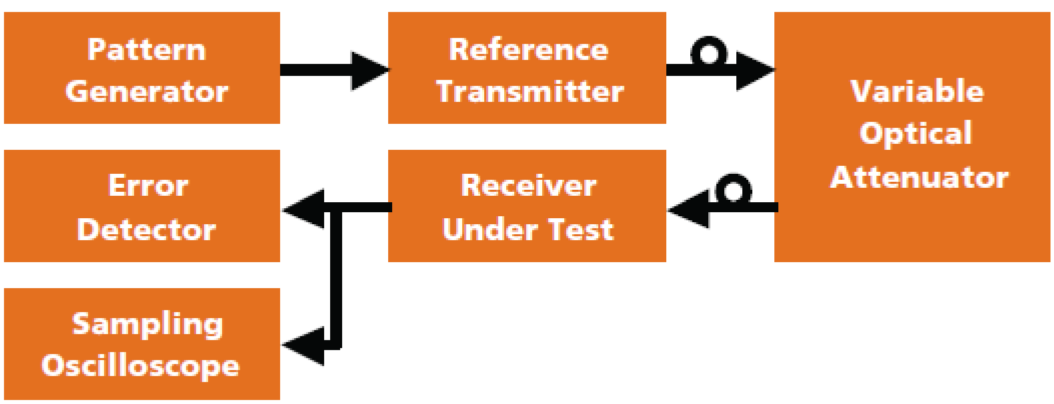


Figure 25 – Optical Receiver test bench

8.1.1 Receiver Sensitivity Testing

The receiver sensitivity is a parameter that indicates the lowest optical power that must be present for the receiver to detect the signal error free. Receiver sensitivity testing is performed by taking bit error ratio (BER) measurements at specific optical power levels and then performing a curve fit to these data points. SMPTE ST 297 specifies a bit error ratio of $<10^{-12}$ – $<10^{-14}$ recommended — with the SDI Matrix checkfield signal, so it is necessary to extrapolate the curve to this level to keep the test time reasonable.

An example of a BER curve is shown in Figure 26. The red data points are measured while the extrapolated data points are in green.

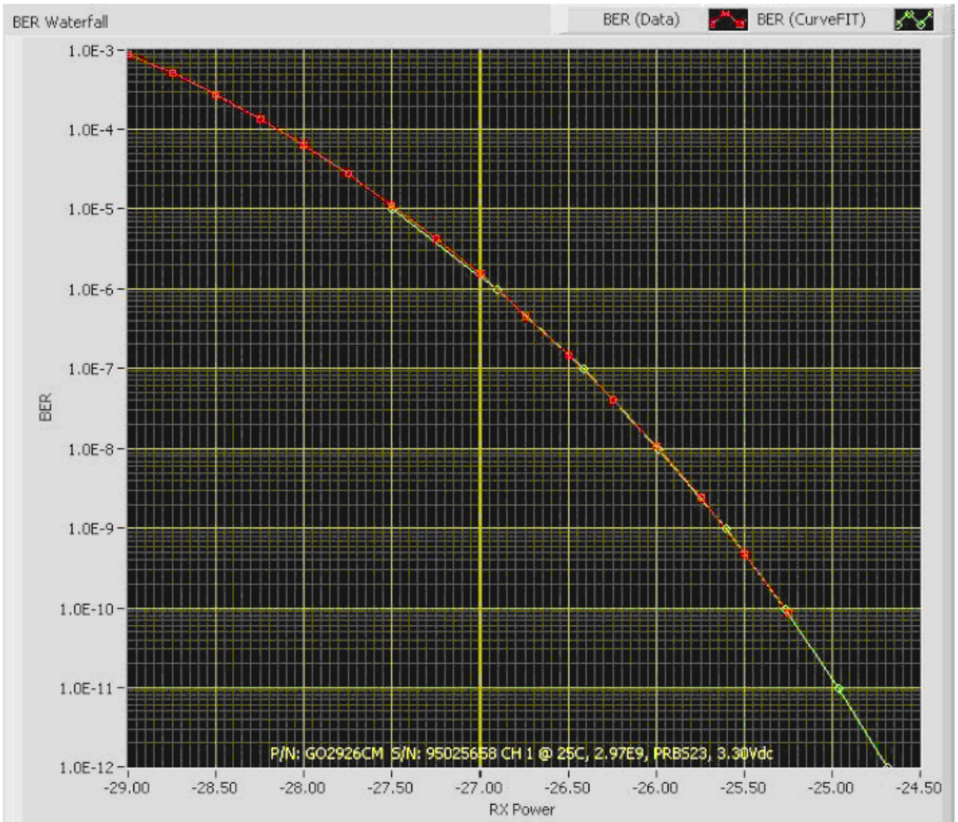


Figure 26 – BER waterfall graph for receiver sensitivity

To take these BER measurements the optical power of the channel under test is first set to a low power level to allow a quick determination of error ratio. After each measurement the optical power is increased by 0.25dB while recording the error ratio until the BER is better that $1x\ 10^{-10}$. At this point the measurements are stopped and the sensitivity point for BER $1x\ 10^{-12}$ is determined by extrapolation.

There is a pathological penalty in receiver sensitivity which can vary greatly depending on receiver design. It is important therefore to repeat the sensitivity measurements with both PRBS and pathological data patterns.

Receiver sensitivity is also highly dependent on the reference transmitter's specifications and performance with pathological data patterns.

8.1.2 Receiver Overload Testing

Overload is a critical specification as it determines how well a receiver will interoperate with transmitters over short runs of fiber. SMPTE ST 297 specifies a preferred overload level of 0 dBm. A very large proportion of SDI optical transmitters deployed today have a maximum specified launch power of 0 dBm, and in CWDM systems the optical transmit power my be as high as +4 dBm, so it is wise to demand that all optical receivers have a minimum 0 dBm overload to ensure robust performance over short runs of fiber.

The overload level of a receiver can be determined by varying the input power to the receiver and monitoring the bit error ratio and the electrical eye diagram from the receiver. Testing requires the use of a high power transmitter in order to provide sufficient optical power after the insertion loss of the Variable Optical Attenuator (VOA) to exceed the overload spec of the receiver.

A typical eye diagram of a receiver above its overload limit is shown below. A downstream reclocker is unlikely to be able to recover this signal without error because of the considerable jitter and the high DCD (Duty Cycle Distortion), or crossing point present in the waveform.

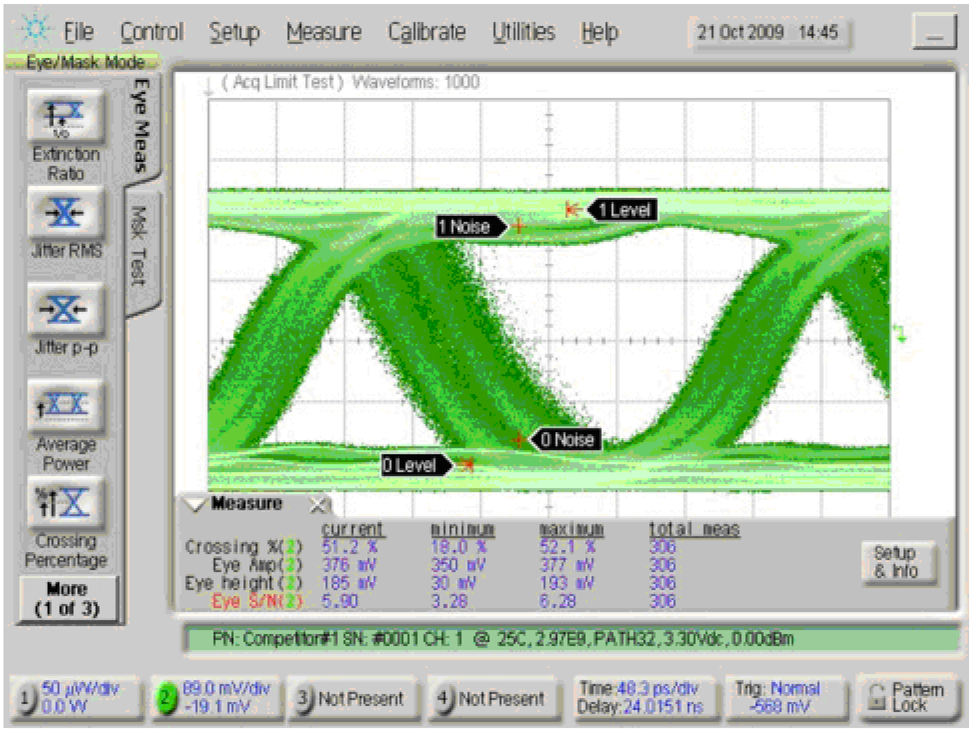


Figure 27 – Receiver in overload

8.1.3 Receiver Jitter Testing

The sensitivity and overload testing described above considers the extremes of the receiver's operating range, but it is also important to validate the performance in the middle of the operating range. Plotting the jitter versus input power across the operating range can reveal whether the optical receiver suffers from jitter peaking. This is a common problem with many optical receivers that are designed with traditional datacom components. An example jitter plot with 3 Gb/s pathological pattern for two different receivers is given in Figure 28. The robust receiver, which was designed with components intended for optical SDI applications, shows an expected slight decline in jitter as the optical power increases. The marginal receiver exhibits jitter peaking centered at -13 dBm, which can result in bit errors at the system level.

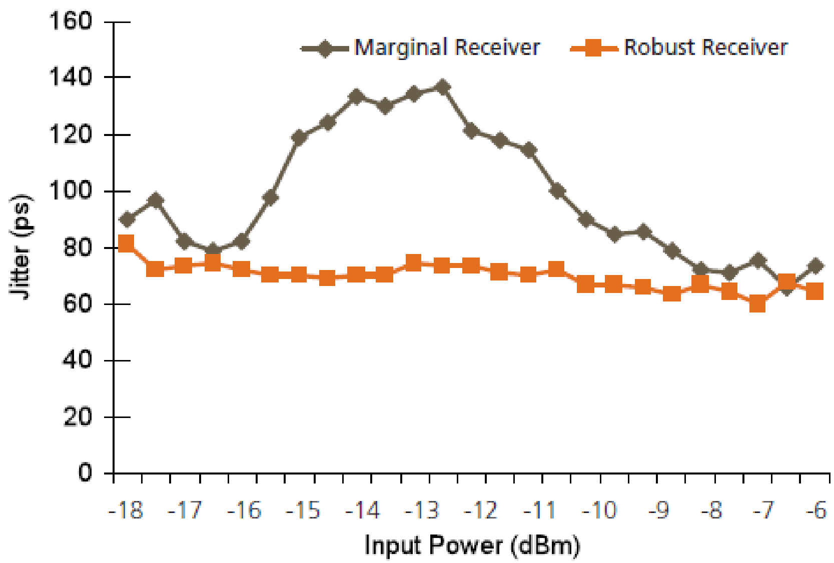


Figure 28 – Analyzing jitter across the full power specification

8.2 Transmitter Testing

The performance of an optical transmitter is best evaluated by using a pattern generator and a high-speed sampling oscilloscope with optical input capability.

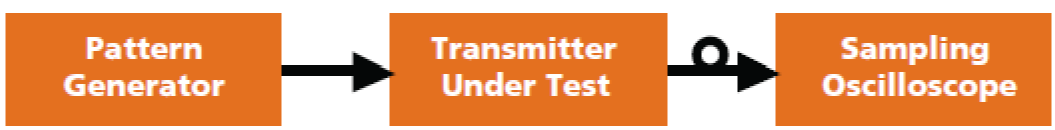


Figure 29 – Typical bench set up for transmitter testing

The key parameters to measure include optical power, extinction ratio, jitter and rise/fall time. An example of an eye diagram of the transmitter is shown below depicting extinction ratio (ER), and rise and fall times (t_{rise}, t_{fall}).

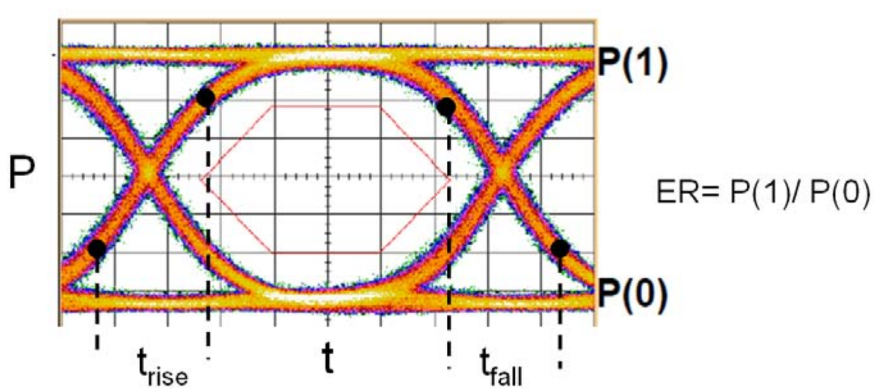


Figure 30 – Eye diagram

Evaluating the transmitters over voltage and temperature corners is also recommended as some lasers can vary significantly. The eye diagrams of two different transmitters at both nominal voltage and at a corner voltage is shown in Figure 31.

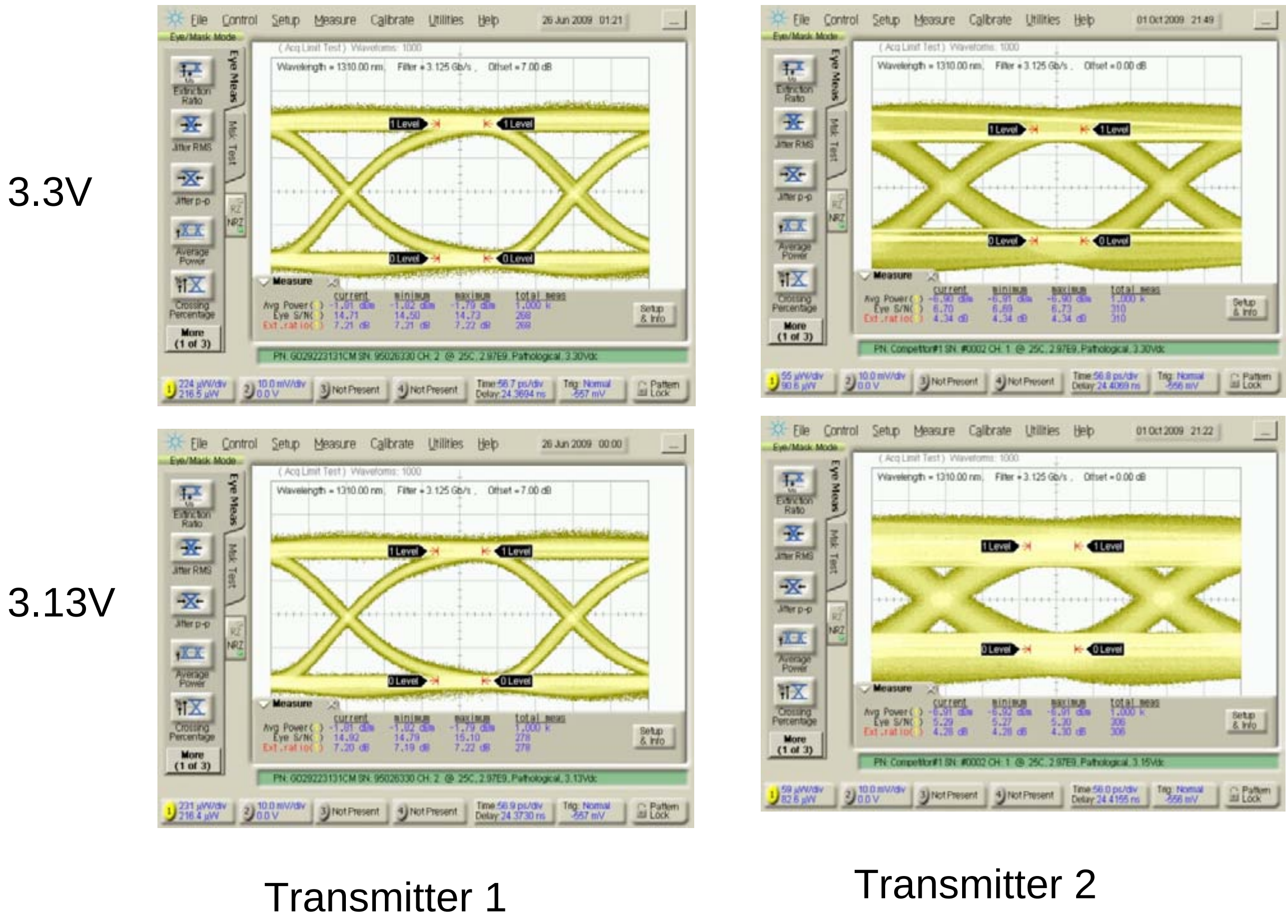


Figure 31 – Transmitter eye diagrams of a robust optical transmitter vs. a marginal transmitter

Transmitter 2 demonstrates a large dependency on supply voltage. At the lower end of the supply voltage the eye has degraded considerably. In contrast, transmitter 1 shows very little dependence on supply voltage.

Transmitters can show similar dependencies over temperature as well, evaluation at different operating temperatures must also be performed.

8.3 System Testing

Careful evaluation of each component is necessary and recommended in the evaluation of an optical system.

However, the performance of each component in isolation is not representative of a real system environment. Testing that is more representative of a system environment would include:

- A non-ideal data source with more jitter
- Dispersion of the signal over the optical fiber
- A reclocker in the receive chain

A test bench for system testing is given in Figure 32.

The pattern generator used in the system test bench includes a delay control input (DCI). By connecting a function generator to the DCI, it is possible to introduce controlled jitter in the input to the optical transmitter.

In a real system, this jitter could result from dielectric and conductor skin effects in FR4 PCB traces, impedance discontinuities, switching noise, etc. A rule of thumb used in optical data communications systems is that the system will be error free with 0.2 UI of total jitter into the transmitter input.

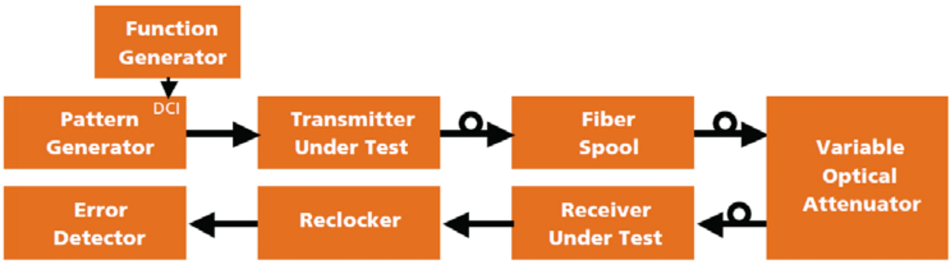


Figure 32 – Typical test bench setup

When the transmitter/receive pairs from the previous examples are exercised in this setup with a 3 Gb/s pathological pattern and 0.2 UI of input jitter over 100m of fiber, the results shown in Figure 33 are achieved.

As previously indicated, the marginal setup does not exhibit error free performance across the receiver’s dynamic range. The errors at the high input power are due to the poor overload performance seen in the receiver testing. The errors in the middle of the operating range are primarily the results of the jitter peaking in this receiver.

Factoring in different output powers from optical transmitters from different manufacturers and different links with different loss profiles, it is easy to understand why SMPTE ST 297 requires a wide preferred receiver operating range of -17 dBm to 0 dBm.

Anything other than error-free performance across this entire range could lead to interoperability issues or difficulty provisioning links where system components from different vendors are mixed and matched. Even worse, if a link is provisioned on the edge of such an error region, a small change in conditions could push it over the edge and compromise the link integrity.

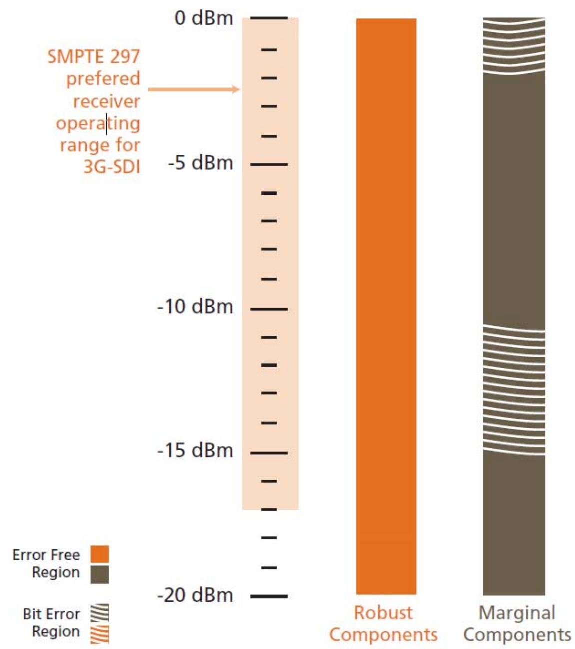


Figure 33 – **System testing results**

9 Safety and Regulatory Requirements

Laser safety: In various jurisdictions, standards bodies, legislation, and government regulations define classes of laser according to the risks associated with them, and define required safety measures for people who could be exposed to those lasers.

Lasers have been classified by wavelength and maximum output power into four main classes as defined by the IEC 60825-1 standard. Lasers used in fiber optics systems are for the most part, Class 1 lasers. Class 1 lasers are low powered devices that are considered safe from all potential hazards under normal use. However, since most wavelengths are in the infra-red band, they are invisible to the human eye so that there is no eye aversion response when subjected to the laser output. Care must therefore be taken with Class 1 lasers although there is little risk of a health impact.

Reliability standards: The telecom industry, which is a mature consumer of optical devices, demands that suppliers qualify their product to the requirements outlined in Telecordia GR-468-CORE. This specification defines the reliability tests that optoelectronic manufacturers must perform on their products to prove that they will be reliable in a field deployment. To ensure reliable links, it is recommended that components used in an optical system are qualified to the GR-468-CORE document.

Annex A Simple Optical Transmitter Design (Informative)

A block diagram of a simple optical transmitter is shown in Figure A.1.

A laser driver provides a bias current and a modulation current to drive the laser, and also receives information on optical power from a monitoring photo diode (MPD).

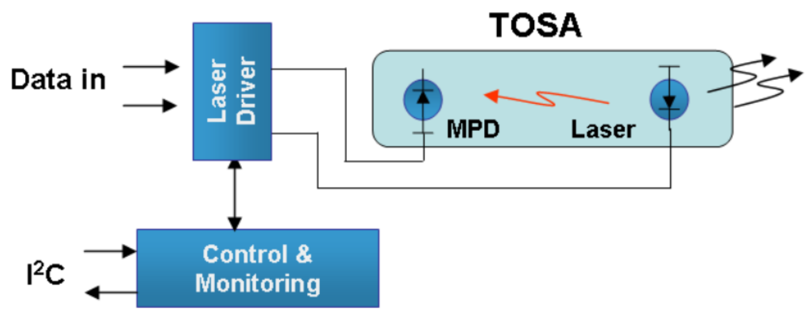


Figure A.1 – Transmitter Block Diagram

The laser and MPD are packaged together in a TOSA (Transmitter Optical Sub-Assembly). An example of a TOSA can be seen in Figure A.2.

Information is fed-back to a control chip for monitoring and control. This is typically accessed through an I2C interface.

Figure A.2 – TOSA

Although semiconductor lasers can be modulated quite readily, all lasers have a non-linear response requiring a minimum threshold current which must be achieved to ensure excitation sufficient to generate a laser output. Figure A.3 depicts the power curve for an ideal semiconductor laser with an idealized "knee" at the threshold current I_{th}. In reality the linear excitation region of the laser does not begin until slightly higher than the threshold current, and the laser must be biased higher than this threshold for reliable operation. The bias current and the modulation current are adjusted to set output power and extinction ratio.

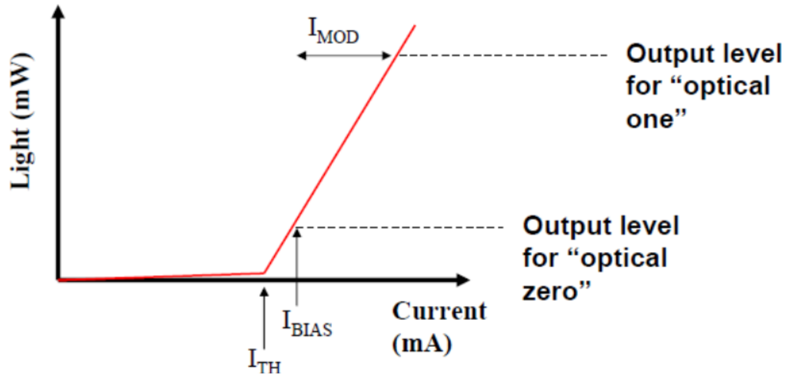


Figure A.3 – Typical L-I curve for diode lasers.

The characteristics of the laser changes with age and temperature and thus a control loop is required to maintain performance. To achieve this control, a small amount of optical power (~1%) is fed back to a monitoring photodiode which sends information on average optical power back to the laser driver. The control loop monitors this and adjusts the bias current and modulation current to keep the average output power and extinction ratio within a constant range.

As AC coupling is used in optical transmitters, a low frequency cutoff is imposed. Careful design must be considered for optical SDI transmitters to ensure error free operation with pathological content.

Annex B Simple Optical Receiver Design (Informative)

An optical receiver consists of a photo-detector (either an APD or PIN), a Transimpedance Amplifier (TIA), a limiting amplifier and a control chip as shown in Figure B.1. The TIA and photo-detectors are packaged in a ROSA (Receive Optical Sub-Assembly). The ROSA is packaged very similarly to the TOSA and assembled in the SFP (or similar) module.

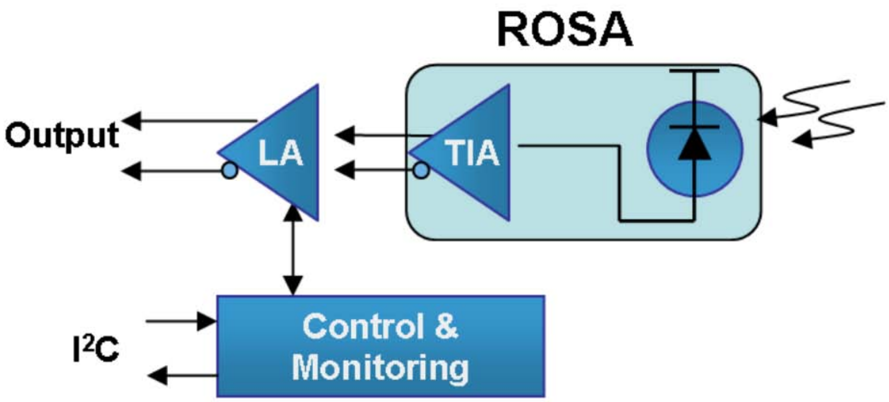


Figure B.1 – Receiver Block Diagram

The photo-detector provides a current to the TIA which converts the small current to a voltage. The TIA amplifies and automatically limits the voltage to a fixed level regardless of the optical input power.

DC offset cancellation which occurs in the TIA and Limiting amplifier, can be an issue for signals which contain a DC imbalance, such as the pathological SDI signal. Selection of components designed for pathological data is recommended for video receivers. The use of devices designed for datacom applications can result in bit errors and other link issues.

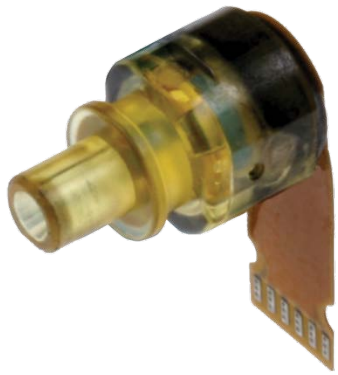


Figure B.2 – ROSA

Annex C Bibliography (Informative)

Note: All references in this document to other SMPTE documents use the current numbering style (e.g. SMPTE ST 259:2008) although, during a transitional phase, the document as published (printed or PDF) may bear an older designation (such as SMPTE 259M-2008). Documents with the same root number (e.g. 259) and publication year (e.g. 2008) are functionally identical.

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IEC 60825-1 (2001-08), including Amendment 1, Safety of Laser Products, Equipment Classification Requirements, and User's Guide

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SFF-8472 Specification for Diagnostic Monitoring Interface for Optical Transceivers

Telecordia GR-468-CORE Reliability Assurance for Optoelectronic Devices

Annex D Glossary of Terms (Informative)

Absorption: That portion of optical attenuation in optical fiber resulting from the conversion of optical power to heat. Caused by impurities in the fiber such as hydroxyl ions, absorption has an effect only at certain wavelengths. Together with scattering, absorption forms the principal cause of the attenuation in an optical waveguide.

Acceptance Angle: The half-angle of the cone within which incident light is totally internally reflected by the fiber core at the core-cladding interface. The Acceptance Angle is equal to sin-1(NA), where NA is an abbreviation for Numerical Aperture.

Adapter: A mechanical device designed to align and join fiber optic connectors. Often referred to as a coupler or bulkhead.

Angle of Incidence: The angle between an incident ray and the normal to a reflecting surface.

APC: Abbreviation for Angled Physical Contact. A style of fiber optic connector manufactured or polished with a 5°-15° angle on the connector tip for the minimum possible back reflection.

Attenuation: The reduction of average optical power in an optical waveguide. The main causes are scattering and absorption, as well as optical losses in connectors and splices. This term is normally expressed in decibels (dB). Attenuation (also known as loss) is expressed by: x dB = -10 log10 (Po/Pi) where Pi is the optical power measured at the input and Po is the optical power measured at the output. Since Po is less than Pi, a negative sign is placed before the 10 to yield a positive number for x.

Attenuation Coefficient: The rate of optical power loss with respect to distance along the optical fiber, usually measured in decibels per kilometer (dB/km) at a specific wavelength. The lower the number, the better the fiber.

Attenuator: A passive optical element that reduces intensity of an optical signal passing through it without otherwise affecting the signal.

Avalanche Photodiode (APD): A photodiode designed to take advantage of avalanche multiplication of photocurrent. As the reverse-bias voltage across the diode junction approaches the breakdown voltage, hole-electron pairs created by absorbed photons acquire sufficient energy to create additional hole-electron pairs when they collide with ions; thus a multiplication or signal gain is achieved.

Axial Ray: A light ray that travels along the central axis of an optical fiber.

Backscattering: The process whereby a small fraction of light that is scattered and deflected out of the original direction of propagation in the optical waveguide suffers a reversal of direction and propagated directly back toward the transmitter.

Bandwidth: The lowest frequency at which the magnitude of the waveguide transfer function decreases to 3 dB (optical power) below its zero frequency value. This is often referred to as the “3 dB Bandwidth.” The Bandwidth will be a function of the length of the waveguide, but can not be directly proportional to the length.

Bandwidth-Length Product: Used for determining a fiber’s ability to transfer a signal of a given bandwidth and distance, the Bandwidth-Length product is equal to the product of the length of the fiber in kilometers and the maximum 3 dB bandwidth that the fiber can sustain in megahertz or gigahertz at a particular optical wavelength.

Beam Splitter: A device used to divide or split an optical beam into two or more separate beams.

Bend Radius: The smallest radius an optical fiber or fiber cable can be bent before causing excessive attenuation or fiber breakage.

Bending Loss: Attenuation that occurs at the location where a fiber is bent around a small radius.

BER (Bit Error Ratio): In digital applications, the ratio of bits received in error to bits sent. BERs of one errored bit per billion $1x10^{-9}$ sent are typical in fiber optic systems.

Buffer: Material used to protect optical fiber from physical damage, providing mechanical isolation and protection. Fabrication techniques include tight or loose tube buffering, as well as multiple buffer layers.

Butt Splice: The result of permanently or semi-permanently coupling two fibers end to end without using a de-mateable connector.

Center Wavelength: The nominal central wavelength of a laser or the central point between the two half-amplitude wavelengths of an LED.

Chromatic Dispersion: Spreading of a light pulse caused by the difference in refractive indices at different wavelengths. This spreading reduces the effective bandwidth of the fiber by affecting the rise/fall times of digital signals at the optical receiver.

Cladding: The dielectric material surrounding the core of an optical fiber. Cladding features a lower refractive index than the core material, trapping light in the core and causing it to travel down the length of the fiber.

Coarse Wavelength Division Multiplexing (CWDM): CWDM combines up to eight widely-spaced optical carrier frequencies on a single fiber, typically at a lower cost than Dense Wavelength Division Multiplexing systems because of relaxed tolerances on lasers and WDM couplers.

Coherent Light Source: A light source in which the amplitude and phase of all waves is exactly identical. Lasers are examples of Coherent Light Sources.

Core: The central region of an optical fiber through which light is transmitted, possessing a higher index of refraction than the cladding surrounding it.

Coupler (Optical Coupler): An optical component used to split or combine optical signal power. Some examples of Couplers are "Splitters," "T-couplers," "2x2s," or "1x2s".

Coupling Loss: The power loss suffered when coupling light from one optical device to another.

Coupling Ratio: The ratio, in percentage, of optical power from one output port of an optical coupler to the total optical coupler output power.

Critical Angle: The smallest angle from the fiber axis at which a ray is totally reflected at the core/cladding interface.

Cut-off Wavelength: The shortest wavelength at which a single-mode fiber will operate as such.

Dark Current: The external current that, under reverse-bias conditions, flows in a photo-detector when there is no incident radiation.

Data Rate: The maximum number of bits of information that can be transmitted per second across a data transmission link. Often expressed as Megabits per second (Mb/s) or Gigabits per second (Gb/s).

Decibel (dB): The standard unit of measurement that expresses relative gain or loss of optical or electrical power on a logarithmic scale as per the formula dB = 10 log10(P1/P2), where P1 and P2 represent the two power levels of interest.

Dense Wavelength Division Multiplexing (DWDM): DWDM combines numerous closely-spaced wavelengths in the 1550nm region onto a single optical fiber. Wavelength spacing's are specified at 100 GHz or 200 GHz.

Detector: A transducer that provides an electrical output current in response to an incident optical power. The output current depends on the amount of light received and the type of device.

Detector Damage Threshold: The guaranteed maximum power level the detector can receive without being damaged.

Dispersion: Temporal spread of the signal in an optical waveguide. Dispersion consists of various components: modal dispersion, material dispersion, and waveguide dispersion. As a result of its dispersion, an optical waveguide low-pass filters transmitted signals.

Dispersion Compensating Fiber: A fiber that has dispersion opposite of other fibers in a transmission system, thus compensating for dispersion effects in other fibers.

Dispersion Shifted Fiber: A type of single-mode fiber tailored to exhibit zero dispersion near 1550 nm. This fiber type works very poorly for DWDM applications because of high fiber nonlinearity at the zero-dispersion wavelength.

Extinction Ratio: Regarding LEDs and laser diodes, the Extinction Ratio is the ratio of the power emitted when sending a low signal (minimum power) to the power transmitted when sending a high signal (maximum power).

Extrinsic Losses: Losses that are caused by imperfections in the mechanical connection or splicing of two fibers. See Intrinsic Losses.

Ferrule: A component of a fiber optic connection that rigidly holds a fiber in place and aids in its alignment.

Fiber Optic Link: A fiber optic cable with connectors attached to a transmitter (source) and receiver (detector).

Fresnel Reflection: The reflection, and resultant loss, of a portion of the light incident on a planar surface between two homogeneous media having different refractive indices. Fresnel reflection occurs at the air/glass interfaces at the entrance and exit ends of an optical fiber. Maximum Fresnel reflection losses at an air/glass interface is 4% of the incident light.

Fundamental Mode: The lowest order mode of an optical waveguide.

Graded Index Fiber: An optical fiber with a refractive index that is a parabolic function of the radial distance from the fiber axis, decreasing in the direction from the axis to the cladding.

Incoherent Light: LEDs emit incoherent light, unlike laser diodes, which emit coherent light.

Index Matching Material: A material, often a liquid or gel, whose refractive index is nearly equal to the core index. It can be used to reduce Fresnel reflections from a fiber end face.

Index of Refraction (Refractive Index): The ratio of the velocity of light in free space (a vacuum), to the velocity of light in an optical fiber, the Index of Refraction is always greater than or equal to one.

Insertion Loss: The attenuation caused by the insertion of an optical component, such as a connector or coupler, into an optical transmission system.

Intensity: The square of the electric field strength of an electromagnetic wave. Intensity is proportional to irradiance.

Intensity Modulation: A modulation scheme in which the optical power intensity of a source varies with a modulating signal. Intensity Modulation is often used in digital transmission systems where digital ‘ones’ and ‘zeros’ are represented by turning a laser or LED on and off.

Intermodal Distortion: Waveform distortion in multimode fiber systems due to propagation of multiple optical modes in such systems and the subsequent temporal dispersion of light propagating in these multiple optical modes.

Integrated Optical Components/Circuits (IOCs): External optical devices that perform signal processing on light transmitted through waveguides. IOCs contain waveguides that structure and confine the propagating light to a region with one or two very small dimensions, of the order of the wavelength of light. A common material used in the fabrication process of an IOC is Lithium Niobate (LiNbO2).

Intrinsic Losses: Losses inherent in optical fiber splices that are caused by minute differences between the fibers being spliced. See Extrinsic Losses.

Irradiance: Power density at a surface through which radiation passes at the radiating surface of a light source or at the cross section of an optical waveguide. The normal unit is Watts per centimetre squared, or W/cm^2.

Jumper Cable: A fiber optic cable, fitted with de-mateable connectors, which is of limited length. Jumper cables are used to interconnect two pieces of fiber optic equipment and/or other fiber optic cables.

Laser Diode (LD): Semiconductor diode, which emits coherent light when forward biased above a threshold current.

Launch Angle: Angle between the propagation direction of the incident light and the optical axis of an optical waveguide.

Launching Fiber: A fiber that connects a laser or LED to another fiber, typically a jumper cable.

Light Emitting Diode (LED): A semiconductor device that emits incoherent light from a p-n junction when forward biased. Light exits from the junction strip edge or from its surface, depending on the device's structure.

Light: In the laser and optical communication fields, the portion of the electromagnetic spectrum that can be handled by the basic optical techniques used for the visible spectrum extending from the near ultraviolet region of approximately 0.3 micron, through the visible region and into the mid-infrared region of about 30 microns.

Light Waves: Electromagnetic waves in the region of optical frequencies that propagate in a direction normal to the optical wave front.

Link Budget (Optical Link Budget, Link Loss Budget, Power Budget): The range of optical power over which a fiber optic link will operate within performance specifications. It is computed by subtracting the optical power launched into an optical fiber from the minimum optical receiver sensitivity at the link endpoint. A link budget typically accounts for all interconnect panels and jumper cables in the system and permits the system designer a verification of system performance prior to installation.

Macro Bending: Macroscopic axial deviations of a fiber from a straight line that cause light to leak out of the fiber, resulting in optical attenuation.

Material Dispersion: Dispersion resulting from variation of propagation velocity as a function of wavelength in an optical fiber.

Micro Bending: Curvatures of the fiber that involve axial displacements of a few micrometers and spatial wavelengths of a few millimeters. Micro bends cause light to leak out of the fiber and consequently increase the attenuation of the fiber.

Micron: Micrometer (µm). One millionth of a meter ($1x10^{-6}$ m).

Modal Dispersion (Multimode Dispersion): Pulse spreading due to multiple light rays traveling different distances and speeds through an optical fiber.

Modal Noise: Disturbance in multimode fibers fed by laser diodes. It occurs when the fibers contain elements with mode-dependent attenuation, such as imperfect splices, and varies with the coherence of the laser light.

Mode: A single electromagnetic wave propagating in an optical waveguide.

Mode Filter: Used in multimode fiber systems, a Mode Filter strips high-order modes off of the power at the launch end, simulating the mode distribution of light in a fiber as it would be if it were measured hundreds of meters into the fiber. This mode distribution, referred to as the “equilibrium mode distribution,” is valuable when testing optical receivers as it eliminates the need for long pieces of fiber in the receiver test bed.

Monochromatic: Consisting of a single wavelength. In practice, radiation is never perfectly monochromatic but, at best, displays a narrow band of wavelengths.

Multimode Distortion: The signal distortion in an optical waveguide resulting from the superposition of modes with differing delays.

Multimode Fiber: Optical waveguide whose core diameter is large compared with the optical wavelength and in which more than a single mode is capable of propagation.

Nanometer (nm): One billionth of a meter (1x10-9m).

Noise Equivalent Power (NEP): The RMS value of optical power which is required to produce an RMS signal-to-noise ratio of 1. Noise Equivalent Power is an indication of a noise level that defines the minimum detectable signal level.

Non Zero Dispersion Shifted Fiber (NZDSF): A dispersion-shifted single-mode fiber that exhibits near the 1550 nm window, but outside the window actually used to transmit signals, maximizing fiber bandwidth while minimizing the effect of fiber nonlinearities on the signal being transmitted.

Numerical Aperture (NA): A measure of the range of angles of incident light transmitted through a fiber. NA is determined by the differences in index of refraction between the core and the cladding.

Optical Fiber: Any filament or fiber made of dielectric materials, which guide light.

Optical Time Domain Reflectometer (OTDR): A device that tests a fiber by transmitting an optical pulse through the fiber and the measuring the resulting backscatter and reflections to the input as a function of time. Useful in estimating attenuation coefficient as a function of distance and identifying defects and other localized losses.

Optoelectronic: Any device that functions as an electrical-to-optical or optical-to-electrical transducer.

Optoelectronic Integrated Circuits (OEICs): Combine electronic and optic functions in a single chip. Peak Wavelength: The wavelength at which the optical power of a source is at a maximum.

Photocurrent: The current that flows through a photosensitive device, such as a photodiode, as the result of exposure to optical power.

Photodiode: A semiconductor diode that produces photocurrent by absorbing light. Photodiodes are used for the detection of optical power and for the conversion of optical power into electrical current.

Photon: A quantum of electromagnetic energy.

Physical Contact Connector: A type of optical connector that maintains physical contact between fibers mounted in ferrules so as to minimize Fresnel reflection effects at the connector enfaces.

Pigtail: A short length of optical fiber for coupling optical components. It is usually permanently fixed to the component at one end and connected with a de-mateable connector at the other end.

PIN-FET Receiver: Optical receiver with a PIN photodiode and low noise amplifier with a high impedance input, followed by a Field-Effect Transistor (FET).

PIN Photodiode: A diode with a large intrinsic region sandwiched between p-doped and n-doped semiconducting regions. Photons entering this region create electron-hole pairs that are separated by an electric field and swept away by a bias current, thus generating an electric current in the load circuit that varies depending on the intensity of light impinging on the intrinsic region of the diode.

UPC / SPC: Abbreviation for Ultra Physical Contact / Super Physical Contact. A style of fiber optic connector manufactured or polished with a convex rounded finish allowing the fibers to touch on a high point near the fiber core where light travels.

Ray: A geometric representation of a light path through an optical medium; a line normal to the wave front indicating the direction of radiant energy flow.

Rayleigh Scattering: Scattering by refractive index fluctuations (inhomogeneities in material density or composition) that are small with respect to wavelength.

Receiver: A detector and electronic circuitry that changes optical signals into electrical signals.

Receiver Overload: The maximum optical power allowed by a receiver for acceptable Bit Error Rates. In the case of digital signal transmission, the mean optical power is usually quoted in Watts or dBm (decibels referenced to 1 milliwatt).

Receiver Sensitivity: The minimum optical power required by a receiver for acceptable Bit Error Rates. In the case of digital signal transmission, the mean optical power is usually quoted in Watts or dBm (decibels referenced to 1 milliwatt).

Reflection: The abrupt change in direction of a light beam at an interface between two dissimilar media so that the light beam returns into the media from which it originated.

Reflectance: The ratio of power reflected back to the incident power at a connector junction/interface or other component or device, usually measured in decibels (dB). Reflectance is stated as a negative value; e.g., -30 dB. A connector that has a better reflectance performance would be a -40 dB connector or a value less than -30 dB. The terms Return Loss, Back Reflection, and Reflectivity are also used in the industry to describe device reflections, but stated as positive values.

Refraction: The bending of a beam of light at an interface between two dissimilar media or in a medium whose refractive index is a continuous function of position (graded index medium).

Refractive Index: The ratio of the velocity of light in a vacuum to that in an optically dense medium.

Repeater: In a light wave system, an optoelectronic device or module that receives an optical signal, converts it to electrical form, amplifies or reconstructs it, and retransmits it in optical form.

Responsivity: The ratio of detector output to input, usually measured in units of amperes per watt (or microamperes per microwatt).

Return Loss: See Reflectance.

SC Connector: A type of connector used on a fiber optic cable that employs a rectangular cross section of molded plastic. It has a push–to-insert and pull-to-remove locking mechanism instead of threaded coupling, preventing rotational misalignment. An audible click indicates that the connector is fully engaged.

Single Mode Fiber: Optical fiber with a small core diameter in which only a single mode, the fundamental mode, is capable of propagation. This type of fiber is particularly suitable for wideband transmission over large distances, since its bandwidth is limited only by chromatic dispersion.

Source: The means (usually LED or laser) used to convert an electrical information carrying signal into a corresponding optical signal for transmission by an optical waveguide.

Splice: A permanent joint between two optical waveguides.

Spontaneous Emission: This occurs when there are too many electrons in the conduction band of a semiconductor. These electrons drop spontaneously into vacant locations in the valence band, a photon being emitted for each electron. The emitted light is incoherent.

ST Connector: A type of connector used on fiber optic cable utilizing a spring-loaded twist and lock coupling similar to the BNC connectors used with coax cable.

Step Index Fiber: A fiber having a uniform refractive index within the core and a sharp decrease in refractive index at the core/cladding interface.

Stimulated Emission: This occurs when photons in a semiconductor stimulate available excess charge carriers, causing the emission of more photons. The emitted light is identical in wavelength and phase with the incident coherent light.

T (or tee) Coupler: A coupler with three ports.

Threshold Current: The driving current above which the amplification of the light wave in a laser diode becomes greater than the optical losses, so that stimulated emission commences. The threshold current is strongly temperature-dependent.

Total Internal Reflection: The total reflection that occurs when light strikes an interface at angles of incidence greater than the critical angle.

Transmission Loss: Total loss encountered in transmission through a system.

Transmitter: A driver and a source used to change electrical signals into optical signals.

Y Coupler: A variation on the T coupler in which input light is split between two channels (typically planar waveguide) that branch out like a Y from the input.

Waveguide: A substance that confines and guides a propagating electromagnetic wave.

Waveguide Dispersion: The component of chromatic dispersion arising from the different speeds light travels in the core and cladding of a single-mode fiber.

Wavelength Division Multiplexing (WDM): Simultaneous transmission of several signals in an optical waveguide at differing wavelengths.

Wavelength Chirp: A shifting of a laser diode's Center Wavelength as it is switched on and off in digital fiber optic systems.

Window: The term window refers to ranges of wavelengths matched to the properties of the optical fiber. The window ranges for fiber optics are the following: First window: 820 to 850 nm, second window: 1300 to 1310 nm, the third window: 1550 nm.

Zero Dispersion Wavelength (Zero Dispersion Point): In a single-mode optical fiber, the wavelength at which material dispersion and waveguide dispersion cancel one another, equating to the point at which fiber bandwidth is maximized.