Cisco Technology Marketing

A Guide to Select Single-Mode Fibers for Optical Communications Applications

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1 Abstract

In recent years progress in fiber optic communications has pushed fiber capacity, defined as the bandwidth*distance product, to its ultimate limits. In particular, amplified Wavelength Division Multiplexing (WDM) systems are limited by a combination of dispersion and nonlinear effects.

To improve fiber capacity in the presence of these fiber impairments, new types of Single Mode Fibers (SMF) have been developed over the years. Many flavors of SMF exist and they differentiate themselves mainly with respect to:

- Chromatic Dispersion (CD) characteristics: absolute values, sign and uniformity across the WDM bands.
- Effective Area.
- Polarization Mode Dispersion (PMD) coefficient.
- Water Peak attenuation (for CWDM applications).

This document aims to explain the differences among the various fiber types and the applications each fiber is best suited for.

As of June 2002 the information contained in this document is believed to be update and correct. Please refer to the most recent vendor data sheets for the latest specifications.

2 Document Map

- Most fiber optics data sheets report the cables to be ITU-T G-SERIES compliant. A good place to start our discussion on the various SMF is the standard ITU-T G-SERIES recommendations. ITU-T G.652, G.653 and G.655 recommendations specify the transmission media characteristics of the three main types of single mode fiber optics cables. We will see how the three categories identified by the ITU-T G recommendations differ and for which application they are optimized. (The G.654 fiber type is a modified version of the G.652 type, where attenuation has been further reduced to below 0.2 dB/Km by using an expensive pure silica structure. The so called Pure Silica Fiber (PSF) is intended for use in very long single span applications to be found in undersea festoons (un-regenerated systems). Since this paper's focus is directed toward terrestrial applications, we will not further develop the discussion on G.654 fiber type.

- Subsequently we will review how the major fiber vendors interpreted the ITU-T G specifications and most importantly which extra design solutions they adopted to optimize the behavior of the fibers for specific applications.

- Over the course of the document, we'll introduce key concepts of fiber optics on a per need basis, to support and clarify the discussion. (These theoretical sections are identified by a "red ink" headline).

The document can be read at two levels: by skipping the theoretical ("red headline") sections focusing only on the main topic of the document, or by reading also the "red sections" to further explore the details of fiber optic transmission.

Acronyms

The following is a list of acronyms used throughout the document:

CD	Chromatic Dispersion
PMD	Polarization Mode Dispersion
SMF	Single Mode Fiber
DSF	Dispersion Shifted Fiber
NZDSF	Non-Zero Dispersion Shifted Fiber
ZWPF	Zero Water Peak Fiber
MFD	Mode Field Diameter
DWDM	Dense Wavelength Division Multiplexing
FWM	Four Wave Mixing (inter-channel nonlinear effect)
XPM	Cross-Phase Modulation (inter-channel nonlinear effect)
CWDM	Coarse Wavelength Division Multiplexing
TDM	Time Division Multiplexing

3 Standard ITU-T Fiber Optic Cable classification

The Telecommunication Standardization Sector of ITU defined the properties of three single mode fiber categories in the ITU-T G-SERIES recommendations:

ITU-T G.652: Characteristics of a single-mode optical fiber cable.

ITU-T G.653: Characteristics of a dispersion-shifted single-mode optical fiber cable.

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

According to the ITU-T G recommendations there are various differences among the three types of single-mode fibers, but *the main parameter distinguishing them is the Chromatic Dispersion (CD) characteristics*.

In the G.65x recommendations, the fiber properties are often specified in relation to the transmission characteristics of the optical interfaces. Optical interfaces are defined in the following set of ITU-T recommendations:

ITU-T G.691: Optical interfaces for single channel STM-64, STM-256 and other SDH systems with optical amplifiers.

ITU-T G.692: Optical interfaces for multi-channel systems with optical amplifiers.

ITU-T G.957: Optical interfaces for equipments and systems relating to the synchronous digital hierarchy.

In the next two sections we are going to discuss:

- Generic fiber characteristics.
- Chromatic dispersion parameters.

3.1 ITU-T G-65x Fibers: Optical Characteristic (excluding chromatic dispersion)

The tables below underscore the major differences among the "ITU-T G fibers":

- G.652 has two sets of specifications depending on the interface and speed types as defined by the recommendation ITU-T G.957, G.691 and G.692. An additional set of specifications covers the most recent "extended band" fibers, also known as Zero Water Peak Fibers (ZWPFs), where the region between 1285nm and 1625nm allows ITU-T G.957 transmissions.

G.652	Optimized Region (nm)	Mode Field Diameter (µm)	Attenuation Coeff. (dB/km)	Max PMD_Q (ps/$\sqrt{km}$)
G.957 and G.691 up to STM-16	1310	8.6-9.5	1310nm: < 0.5 1550nm: <0.4	N/A
G.957, G.691 and G.692 up to STM-64	1310	8.6-9.5	1310nm: < 0.4 1550nm: <0.35 1625nm: <0.4	0.5
G.957 over **Extended band 1360-1530nm (G.957, G.691 and G.692 up to STM-64 in "standard" bands)**	1310	8.6-9.5	1310nm: < 0.4 1383-1480nm: < than at 1310nm 1550nm: <0.35 1625nm: <0.4	0.5

Table 1, Main Optical Characteristics (excluding Chromatic Dispersion) of ITU-T G.652 fibers

- G.653 has one base category of specification suitable for ITU-T G.691 and G.692 with unequal-channel-spacing systems in the 1550nm band.

G.653	Optimized Region (nm)	Mode Field Diameter (µm)	Attenuation Coeff. (dB/km)	Max PMD_Q (ps/√km)
G.691 and G.692 w/ unequal-channel-spacing @ 1550nm	1550	7.8-8.5	1550nm: 0.35 1300nm: < 0.55	0.5

Table 2, Main Optical Characteristics (excluding Chromatic Dispersion) of ITU-T G.653 fibers

- G.655 defines two sub-categories both supporting ITU-T G.691 and G.692 transmission. The two categories are distinguished with respect to their behavior with G.692 transmission systems: the base category does not specify PMD and the minimum channel spacing is restricted to 200Ghz. The second category allows a minimum channel spacing of 100Ghz and specifies PMD requirements to allow operations at 10Gb/s to at least 400km in length.

G.655	Optimized Region (nm)	Mode Field Diameter (µm)	Attenuation Coeff. (dB/km)	Max PMD_Q (ps/√km)
G.692/min 200Ghz	1550	8-11	0.35	N/A
G.692/min 100Ghz	1550	8-11	1550nm: 0.35 1625nm: 0.4	0.5

Table 3, Main Optical Characteristics (excluding Chromatic Dispersion) of ITU-T G.655 fibers

Optimized Region

Each fiber is optimized for a specific spectral region as reflected by the "Optimized Region" columns in the tables above. The key point is to understand why different fibers are optimized for different regions and how this is achieved. The focus of next section (*"ITU-T G-65x Fibers: Dispersion Characteristic and Applications")* is to describe why there are three flavors of fibers and what makes them "specialized" for different applications.

Mode Field Diameter (MFD)

There are many other physical parameters of the fiber that we did not report in the table, but "Mode Field Diameter" is mentioned because it is an important parameter that indirectly determines the contribution to chromatic dispersion known as waveguide dispersion.

The mode field diameter is also a fundamental parameter influencing the "Effective Core Area", A_{eff}, which determines the nonlinear behavior of the fiber optic cable.

(Keep in mind A_{eff}, because it is the key to understanding the design philosophy behind the Corning LEAF NZDS family of fibers.)

And last but not least single-mode fibers with small mode field diameters show higher coupling losses at connections.

The mode field diameter should not be confused with the core diameter of the fiber.

3.2 Definition of Mode Field Diameter

In an optical signal, not all the light travels through the core of the fiber. The optical power is distributed between the core and the cladding. The "Mode Field" represents the distribution of light through the core and cladding of a particular fiber. The picture below clarifies the concept of MFD and its relationship with the fiber core diameter.

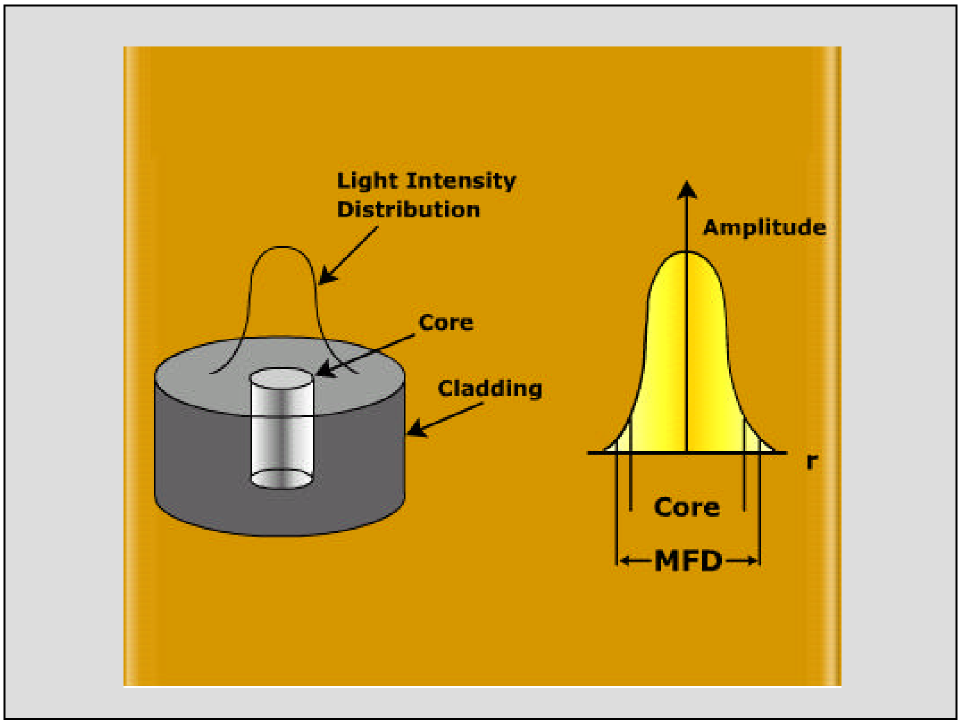

Figure 1, MFD represents how the light is actually distributed in the SMF

3.3 Origins of Chromatic Dispersion

There are two contributions to the chromatic dispersion coefficient D: the first contribution ($D_{Material}$) known as *Material Dispersion* occurs because the refractive index of silica, the material used for fiber fabrication, changes with the optical frequency. Material Dispersion is often confused with the overall Chromatic Dispersion, however a second factor plays a significant role to determine the CD characteristic: *Waveguide Dispersion*.

The contribution of Waveguide Dispersion ($D_{Waveguide}$) depends on fiber parameters like core diameter and core-cladding refractive index difference. The reason is that, since the MFD is larger than the core diameter, *part of the light travels in the cladding and part travels in the core*. Because core and cladding have different refractive indices there is an extra contribution to dispersion. It can be demonstrated that even Waveguide dispersion is wavelength dependent.

It is interesting to note how by altering physical parameters of the fiber like the core diameter or the refractive indices, we can alter the $D_{Waveguide}$ contribution therefore shifting the natural dispersion characteristic of a G.652 fiber and create a G.653 fiber.

$$D = D_{Material} + D_{Waveguide} \qquad (1)$$

3.4 Mode Field Diameter, Effective Core Area and its relationship with nonlinear effects

The strength of nonlinear effects is influenced by various transmission and fiber parameters, among which the Effective Core Area, or A_{eff}, plays a significant role. To understand the reason why, we need to take a step back and refresh the concept of non-linearity in fiber optics.

When we study fiber optic transmission in terms of attenuation and dispersion we assume to operate in linear regime. This means that the Intensity of the signal does not alter the fiber chromatic dispersion and the attenuation characteristics.

Intensity is defined as a ratio between power and an area (milliwatts divided by square microns):

$$I = P/A \quad [W/\mu m^2] \qquad (2)$$

In fiber optic when the signal Intensity grows above certain thresholds, both the attenuation and chromatic dispersion coefficient exhibit deviations from their standard characteristics. In these conditions fiber optics transmission operate in nonlinear regime.

As we notice from (2), the Intensity and therefore the nonlinear behavior of the fiber are enhanced as the Area is reduced. Now it's a matter of understanding which Area we are looking at in fiber optics.

The Intensity of an optical signal is determined by how the optical power is distributed on the circular core of the fiber. Not all the core of the fiber is illuminated. *The illumination area (or the light spatial distribution in the core) is defined as Effective Core Area,* A_{eff}.

<u>*Attenuation*</u>

The first important parameter we need to know when we design a fiber optic network is the attenuation coefficient in our operating window[s].

From the above tables we note how:

- G.652 fibers, although optimized for 1310nm operations, have virtually the same attenuation values at 1550nm as G.653 and G.655.

- G.655 fiber does not recommend attenuation values in the 1300nm window.

Virtually every new fiber commercially available exceeds the ITU-T recommendation in terms of attenuation.

3.5 Fiber Optic Attenuation Coefficient

Figure 2 depicts the typical attenuation characteristic of a single mode fiber. The attenuation coefficient has various contributions in different region of the spectrum. The way the various components of the attenuation add up, creates two favorable windows for optical communication: 1300nm and 1550nm region.

The overall attenuation is determined by the following factors:

1) Silica Material Absorption: Silica, from which fibers are fabricated, absorbs light in the ultraviolet region (UV) and far-infrared (FIR) region.

2) Rayleigh Scattering: simplifying we can describe this fundamental loss mechanism as arising from a scattering effect between the photons and the atoms of the silica. This loss contribution depends on the wavelength as $?^{-4}$, therefore it is dominant at short wavelengths.

3) "Water Peaks": during the fiber-fabrication process, special precautions are taken to ensure that a low level of impurities contaminates the fiber. In standard fiber OH ion impurities are not completely eliminated and they lead to the two absorption peaks near 1230nm and 1380nm. In especially prepared fibers, like the Lucent All-Wave, these water peaks virtually disappear opening up the entire window from 1280nm to 1600nm.

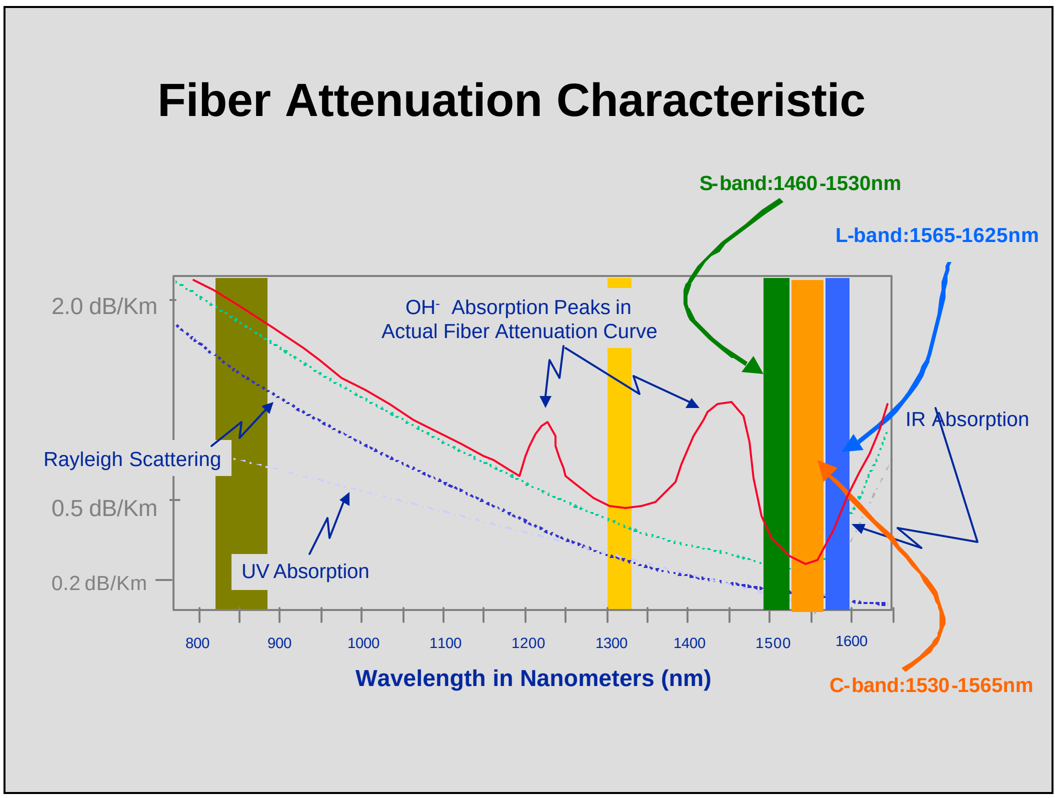

Figure 2, Example of attenuation coefficient of a single-mode fiber.

Polarization Mode Dispersion (PMD) Coefficient

In all the G.65x recommendations, PMD is specified with respect to 10Gb/s transmission systems. A parameter called "PMD Link Design value", or PMD_Q, is used as a statistical metric for the PMD coefficient. A PMD Link design value of 0.5 [ps/vkm] is used in all the ITU-T G recommendation.

3.6 Polarization Mode Dispersion

The Figure below is a quick refresh of the basic concept of PMD.

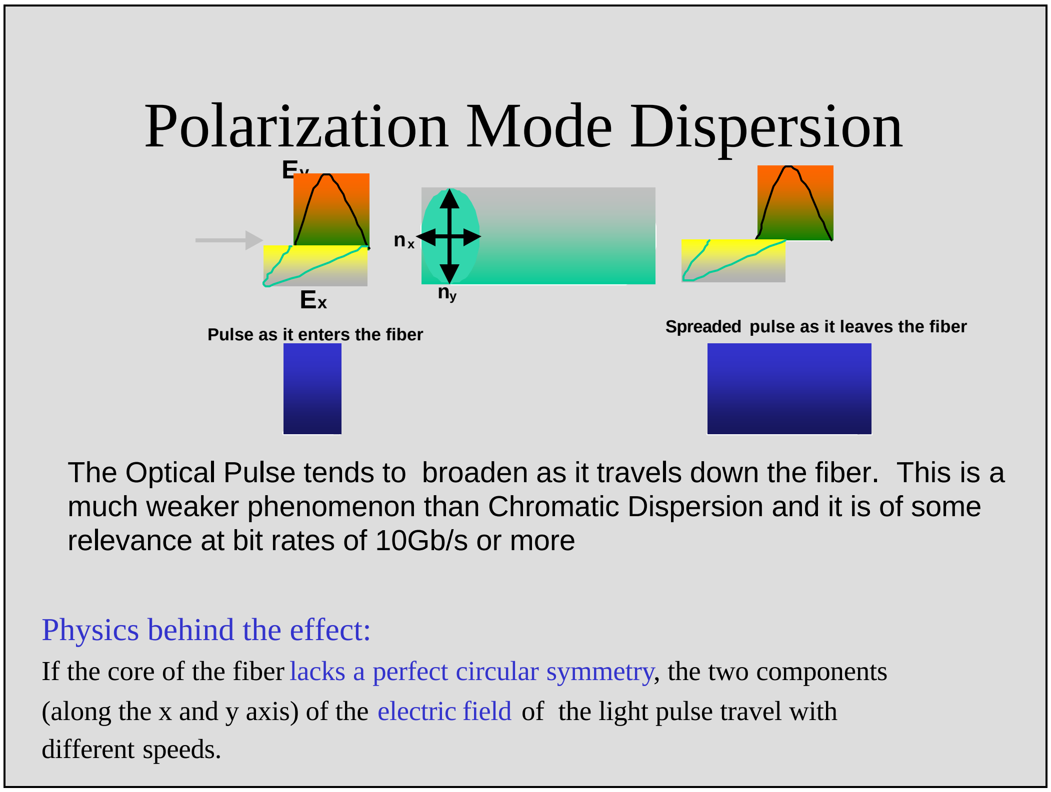

Figure 3, PMD Concept

Actually PMD has a *statistical* and *dynamic* nature and it can vary with temperature, vibrations in the ground and aging. The ability to dynamically compensate PMD will be key to successfully deploying 40Gb/s systems over long distances.

3.6.1 Reading the PMD specification on fiber data sheets: "PMD Link Design" or PMD_Q

PMD, due to its statistical behavior, is probably the most complex fiber parameter to characterize. Only in recent years, with the introduction of 10Gb/s transmission systems, PMD has finally been thoroughly investigated. The initial ITU-T G.65x recommendations "marked" PMD as an issue "under study", whereas the most recent revision of the recommendations provides an in-depth analysis of the statistical nature of PMD.

The ITU-T recommendations introduce a statistical parameter to characterize PMD: the PMD Link Value also known as the PMD_Q.

PMD_Q can be viewed as a statistical metric to measure PMD. *PMD_Q describes the PMD coefficient statistical upper limit of a concatenated link of twenty cables*.

In the fiber data sheets PMD_Q is often referred as "PMD Link Value" or "PMD for cabled fibers". Many vendors specify also the PMD coefficient of an individual fiber.

3.7 ITU-T G-65x Fibers: Chromatic Dispersion Characteristic

3.7.1 ITU-T G.652 Chromatic Dispersion Characteristic

The dispersion characteristic of a single mode G.652 fiber is represented in the picture below.

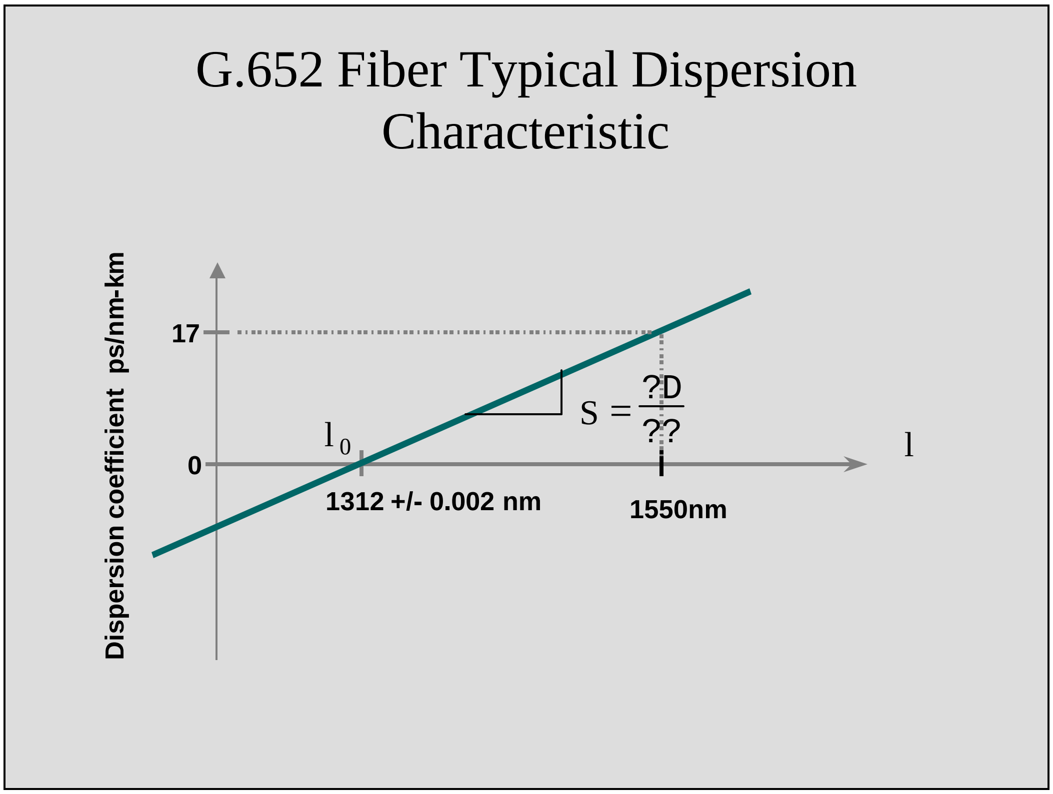

Figure 4, ITU-T G.652 typical dispersion coefficient

The ITU-T recommendation specifies the following dispersion parameters:

G.652 – Chromatic Dispersion Parameters	?0	Typical D [ps/nm*km] /S [ps/km*nm^2] @ 1550nm	S_{omax} [ps/km*nm^2]
	1300nm-1324nm	17/0.056	0.093

Table 4, CD parameters for G.652 fibers

?0: zero-dispersion wavelength; D: Dispersion coefficient; S: Dispersion slope; S_{omax}: Max value of the dispersion slope at ?0.

3.7.2 Understanding the Dispersion Slope (Second Order Dispersion)

The parameter S represents the dispersion slope and is also known as second-order dispersion parameter. In WDM systems it is desirable to have all the channels experience a similar dispersion coefficient in order to reduce the costs associated with dispersion management. For this reason fibers with reduced slope have been developed for multi-channel applications

The S parameter is also important to determine dispersion effects occurring at the zero-dispersion lambda:

According to formula (3), which determines the distance (L_D) a signal can travel before CD degrades the optical pulses, it seems like a signal at the zero-dispersion wavelength (|D| = 0) can travel an infinite distance undistorted.

$$L_D = 1/ B |D| \ ?? \qquad (3)$$

D: dispersion coefficient (ps/km-nm)

??: source linewidth or optical bandwidth (nm)

B: bit rate (1/T where T is the bit period)

However, since the CD slope is non-zero, the "effective" dispersion coefficient experienced by a signal of spectral width ?? is:

$$D = S \ ?? \qquad (4)$$

Substituting (4) into (3) yields $L_D = BS??^2$, which explains why L_D is after all finite even when D = 0 [ps/nm*km].

3.7.3 ITU-T G.653 Dispersion Shifted Fiber - Chromatic Dispersion Characteristic

The dispersion characteristic of a G.653 fiber is represented in **Figure 5**.

As we can see, the dispersion characteristic has been altered compared to a standard single-mode G.652 fiber and now the zero-dispersion wavelength falls at 1550nm instead of 1310nm.

The detailed specification appears in **Table 5**:

G.653 – Chromatic Dispersion Parameters	$?_0$ +/- 50nm	D_{max} [ps/nm*km] at +/- 25nm from 1550nm	S_{omax} [ps/km*nm^2].
	1550nm	3.5	0.085

Table 5, CD parameters for G.653 fibers

$?_0$: zero-dispersion central wavelength; D_{max}: Maximum dispersion coefficient in the specified region; S_{omax}: Max value of the dispersion slope at $?_0$.

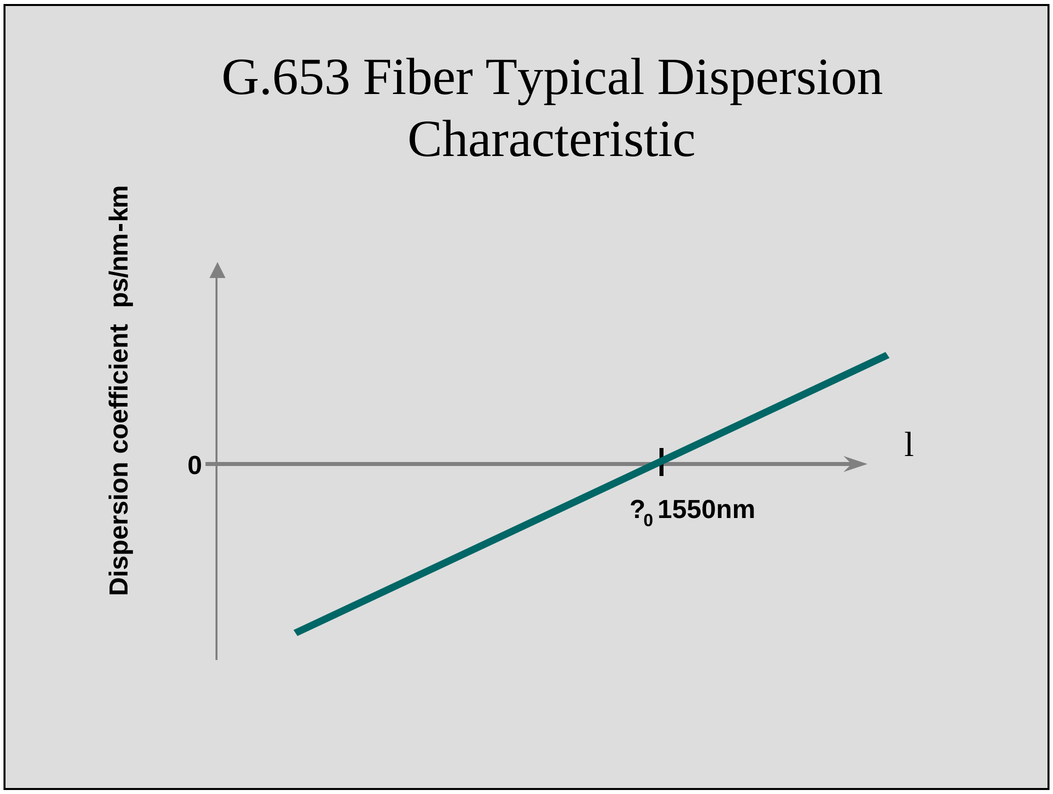

Figure 5, ITU-T G.653 typical dispersion coefficient

When we look at the attenuation (**Figure 2**) and CD (**Figure 4**) characteristics of a standard G.652 fiber, we realize that the best attenuation and dispersion operating points are in different regions: 1550nm and 1310nm.

Dispersion-shifted fibers have been created to take advantage of the best of both worlds: by shifting the zero-dispersion wavelength into the 1550nm band we also operate at the lowest possible attenuation.

A DSF looks like an ideal means to maximize the reach of optical communication systems in the 1550 window. A DSF is indeed suitable for TDM or single-channel applications, however it turns out that having zero-dispersion at 1550nm is a negative condition for DWDM applications*: the "absence" of chromatic dispersion enhances nonlinear impairments like Four Wave Mixing (FWM) and Cross-Phase Modulation (XPM)* basically limiting the ultimate system performance. To counteract the role of nonlinear effects in DWDM systems and still benefit from reduced dispersion in the 1550nm region, a new generation of fibers has been developed: the so called non-zero dispersion shifted (NZDSF) fibers.

3.7.4 Chromatic Dispersion and nonlinear effects

For once, during the course of this section, we will look at Chromatic Dispersion as a positive phenomenon.

It can be demonstrated, that in order to mitigate cross-channel nonlinear effects (FWM and XPM), a certain level of chromatic dispersion is desirable. The explanation of this behavior can be found in the, so called, "walk-off effect".

The "walk-off effect" can be explained by looking at the following two pictures:

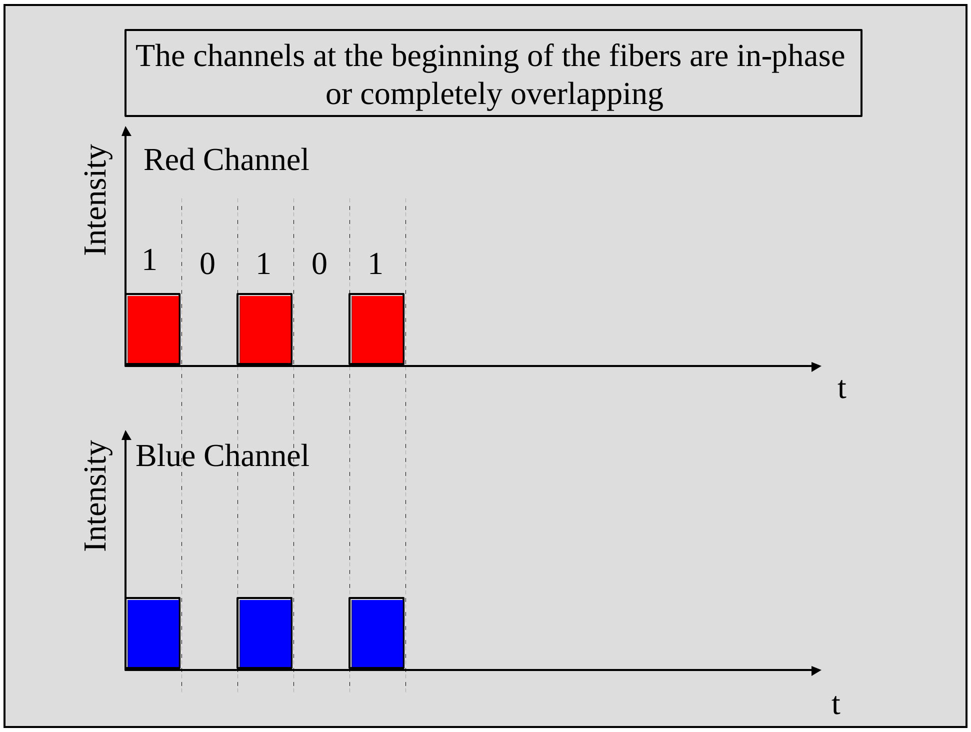

Figure 6, Model of two co-propagating WDM channels at the beginning of the fiber

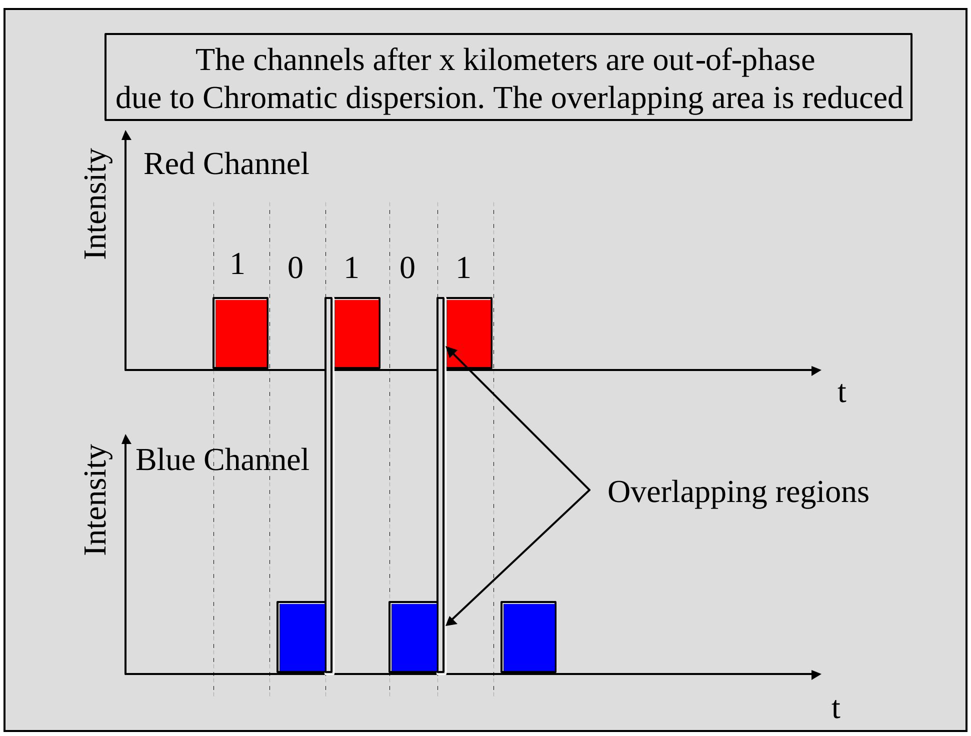

Figure 7, The "walk-off" effect determined by Chromatic Dispersion

Cross-channel nonlinear effects happen when the red and blue bits are synchronized, or, in other words, when their power is overlapping in the time domain (**Figure 6**). Due to CD, the blue and red channels propagate at different speeds and after a while the red-bits sequence tends to drift away (walk-off) from the blue-bits sequence (**Figure 7**).

When the blue and the red bits are no longer in-phase just a portion of their power is overlapping and nonlinear effects are minimized.

In a DSF, close to 1550nm, the blue and red signal speeds are almost the same, keeping the blue bits "in sync" with the red bits, and enhancing nonlinear effects. In a G.652 fiber, high dispersion in the 1550nm region (around 17ps/nm*km) helps to reduce significantly the impact of FWM and XPM.

3.7.5 ITU-T G.655 Chromatic Dispersion Characteristic

The dispersion characteristic of a single mode G.655 fiber is represented in the picture below.

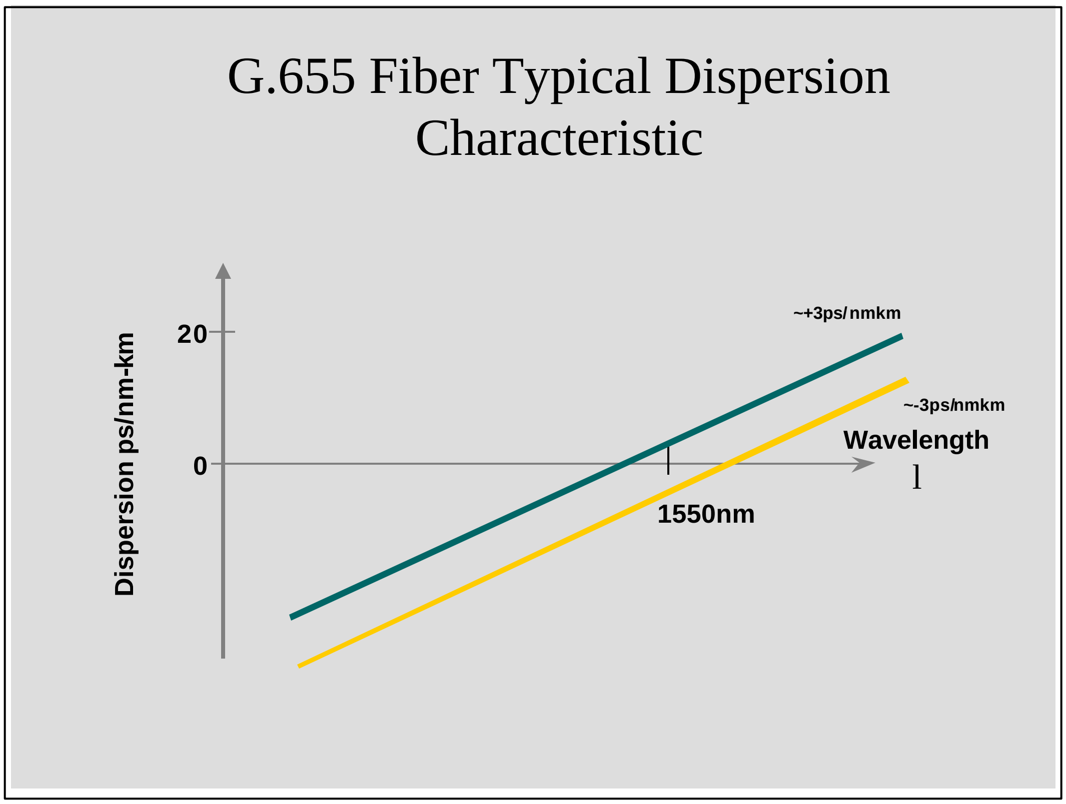

Figure 8, ITU-T G.655 typical dispersion coefficients

Non-Zero Dispersion Shifted fibers are engineered for DWDM applications. The idea behind NZDSF is that we want to have low dispersion in the 1550 region, but not zero. We still need a residual dispersion to mitigate cross-channel nonlinear effects.

The following table details the CD parameters as specified by the G.655 recommendation.

G.655 – Chromatic Dispersion Coefficient Values -G.692/min 200Ghz	$?_{min}$ - $?_{max}$ Wavelength range [nm]	D_{max} [ps/nm*km]	D_{min} [ps/nm*km]	**Sign constant over** $?_{min}$ - $?_{max}$
	1530 - 1565	6	0.1	Positive or Negative

Table 6, CD parameters for G.655 fibers – specification w/ G.692/min. 200Ghz

G.655 – Chromatic Dispersion Coefficient Values - G.692/min 100Ghz	$?_{min}$ - $?_{max}$ Wavelength range [nm]	D_{max} [ps/nm*km]	D_{min} [ps/nm*km]	Sign constant over $?_{min}$ - $?_{max}$	D_{max} - D_{min} [ps/nm*km]
	1530 - 1565	10	1	Positive or Negative	<= 5

Table 7, CD parameters for G.655 fibers – specification w/ G.692/min. 100Ghz

3.8 ITU-T G-65x Fibers: Applications

Each G-65x fiber is optimized for certain applications, thus we first have to define what we mean by "applications". To differentiate among G.65x fibers it is sufficient to introduce the following four applications (later on we'll discuss a more "granular" classification):

- 1310nm Intermediate Reach applications.
- 1550nm Long Reach single channel (such as TDM or 10GE serial) applications.
- 1550nm Dense Wavelength Division Multiplexing (DWDM) applications.
- Coarse Wavelength Division Multiplexing (CWDM) applications.

The table below summarizes which fiber is best suited for which application.

Fiber Type	1310nm IR	1550nm single channel	1550nm DWDM	CWDM
G.652	Optimized	Good	Good	Good
G.652 "Extended band"	Optimized	Good	Good	Optimized
G.653	Good<STM-64	Optimized	Working	Good
G.655	Good<STM-64	Good	Optimized	Good

Table 8, ITU-T G.65x fibers and applications

4 Commercially Available Fiber Optics Cables

Beside the standard specifications it is now time to examine commercially available SMF. The following discussion examines fibers belonging to the G.652, G.653 and G.655 categories. The NZDSF class is the most interesting, because the development is driven by the rapidly evolving DWDM technology. There are many NZDS fibers and it is interesting to note how each vendor tries to optimize the performance by balancing first and second order chromatic dispersion with nonlinear effects.

"Extended Band" fibers are another emerging interesting category, which, by removing the water peak at about 1383nm, effectively open up the possibility to transmit from 1265nm to 1625nm. This fiber is optimized for CWDM applications.

4.1 Choosing the right fiber for the right application

The applications as defined earlier are useful to illustrate the difference between Standard SMF, NZDSF and DSF.

However there are too many SMF types, and in order to pick up the right fiber for our purposes, a more precise definition of applications is required.

With the table below, we start by defining the application landscape and by highlighting which fiber parameters in the data sheets should be considered to optimize each application.

Then we go through a list of fibers data sheets (provided by the vendors) divided by category.

At last, because the vendor specifications are often "worst-case", we also want to present some typical data measured on real fibers.

The table below is an attempt to summarize which fiber types are best suited for specific applications. Based on the fact that not all fibers of the same family (G.652, G.653 and G.655) are created equal, the table below underscores which are the parameters in the data sheets we should ponder when selecting a fiber for a specific task.

Within a category of fiber, the differences can be very subtle because based on very complex transmission design tradeoffs. The indications reported in **Table 9** are generic guidelines to select SMF.

Market Segment	Application	Best SMFs	Application-friendly fiber characteristics
Access up to 40km	Low Speed < 2.5Gb/s 1310nm	G.652	Optimized Attenuation @ 1310nm
	High Speed 10Gb/s 1310nm	G.652	Low Attenuation @ 1310nm Low Dispersion Slope @ 1310nm Typical Zero Dispersion Wavelength
Metro up to 350km (C-band)	Single Channel High Speed (OC-192, 10GE)	G.653	Low Dispersion Slope @ 1550nm Optimized Attenuation @ 1550nm
	Low Density DWDM (>=100Ghz)	G.655 G.652	Low Dispersion Slope C-band Atten. vs Wavelength in the C-band
	High Density DWDM (<= 50Ghz)	G.655	Balance between low dispersion slope and large effective area
	DWDM 2.5b/s Direct Modulation	G.655 "-" G.655 G.652	Negative Dispersion (balance chirp)
	Low Speed (<=2.5Gb/s) CWDM	G.652.Ext. G.652	Optimized Water Peak Attenuation Atten. vs Wavelength across the whole band
Extended Long Haul (up to 2000km) /Submarine Ultra Long Haul (up to 6000km)	High Density DWDM C-band (<=50Ghz)	G.655	Large Effective Area Low Dispersion Slope C-band Relatively Higher dispersion Low PMD
	High Density DWDM L or C+L band	G.655	Large Effective Area Atten. vs Wavelength in the L-band or C+L Relatively Higher dispersion Low PMD
	DWDM C+L+S-band	G.655	Optimizations for the S-band
	Raman Amplification	G.655	Lower Attenuation around 1450 for Raman pump efficiency
	DWDM 40Gb/s	G.655	Low PMD Low chromatic dispersion Low chromatic dispersion Slope

Table 9, Fiber Optics cables and applications

4.2 Standard Single-mode Fibers Optical Specifications

4.2.1 Corning SMF-28 – G.652 compliant

Attenuation @ 1310nm (dB/km)	Premium <= 0.34 Standard <=0.35
Attenuation @ 1550nm (dB/km)	Premium <= 0.20 Standard <= 0.22
Attenuation @ water peak 1383 +/- 3nm	< 2.1dB/km (typical 0.5 db/km)
Attenuation vs Wavelength: 1285-1330nm	Max difference 0.05 db/km (ref. 1310nm)
Attenuation vs Wavelength: 1525-1575nm	Max difference 0.05 db/km (ref. 1550nm)
Mode Field Diameter @1310nm	9.2 +/- 0.4 µm
Mode Field Diameter @1550nm	10.4 +/- 0.8 µm
Typical Core Diameter	8.2 µm
Zero Dispersion Wavelength	1302nm <= $?_0$<= 1322nm
Zero Dispersion Slope	S_0 <= 0.092 ps/km*nm^2
PMD Link Value	<= 0.1 ps/vkm

4.2.2 Alcatel 6900 – G.652 compliant

Attenuation @ 1310nm (dB/km)	<= 0.34
Attenuation @ 1550nm (dB/km)	<=0.24
Attenuation @ water peak 1383 +/- 3nm	< 1.5 dB/km
Attenuation vs Wavelength: 1285-1310nm	Max difference 0.035 db/km
Attenuation vs Wavelength: 1310-1330nm	Max difference 0.03 db/km
Attenuation vs Wavelength: 1525-1550nm	Max difference 0.03 db/km
Attenuation vs Wavelength: 1550-1575nm	Max difference 0.03 db/km
Mode Field Diameter @1310nm	9.0 +/- 0.5 µm
Mode Field Diameter @1550nm	10.2 +/- 1.0 µm
Typical Core Diameter	8.8 µm
Zero Dispersion Wavelength	1300nm <= $?_0$<= 1320nm
Zero Dispersion Slope	S_0 <= 0.092 ps/km*nm^2
PMD Link Value	<= 0.1 ps/vkm

4.2.3 ATT/Lucent – SSMF –G.652

Attenuation @ 1310nm (dB/km)	<= 0.4
Attenuation @ 1550nm (dB/km)	<=0.25
Attenuation @ water peak 1383 +/- 3nm	< 1.5 dB/km
Attenuation vs Wavelength: 1520-1620nm	Max difference 0.05 db/km (Ref. 1550nm)
Mode Field Diameter @1310nm	9.3 +/- 0.5 µm
Mode Field Diameter @1550nm	10.5 +/- 1.0 µm
Typical Core Diameter	8.8 µm
Zero Dispersion Wavelength	1300nm <= ?$_0$<= 1322nm
Dispersion coefficient at 1550nm	18 ps/nm*km
Zero Dispersion Slope @ ?$_0$	S_0 <= 0.092 ps/km*nm^2
Zero Dispersion Slope @ 1550nm	S_0 <= 0.08 ps/km*nm^2
PMD for cabled fiber	<= 0.5 ps/vkm

4.2.4 Lucent Matched Cladding (MC) SMF –G.652

Attenuation @ 1310nm (dB/km)	0.35 - 0.4 (customer specified)
Attenuation @ 1550nm (dB/km)	<=0.21 – 0.3 (customer specified)
Attenuation @ water peak 1383 +/- 3nm	< 2 dB/km
Attenuation vs Wavelength: 1285-1330nm	Max difference 0.1 db/km (Ref. 1330nm)
Attenuation vs Wavelength: 1525-1575nm	Max difference 0.05 db/km (Ref. 1550nm)
Mode Field Diameter @1310nm	9.3 +/- 0.5 µm
Mode Field Diameter @1550nm	10.5 +/- 1.0 µm
Effective Area	87 µm^2
Typical Core Diameter	8.3 µm
Zero Dispersion Wavelength	1300nm <= ?$_0$<= 1322nm
Dispersion coefficient at 1550nm	18 ps/nm*km
Zero Dispersion Slope @ ?$_0$	S_0 <= 0.088 ps/km*nm^2
PMD for cabled fiber	N/A

4.2.5 Sumitomo SMF- Grade A

Attenuation @ 1310nm (dB/km)	0.35

Attenuation @ 1550nm (dB/km)	0.25
Attenuation @ water peak 1383 +/- 3nm	< 2 dB/km
Attenuation vs Wavelength: 1285-1330nm	Max difference 0.1 db/km (Ref. 1330nm)
Attenuation vs Wavelength: 1525-1575nm	Max difference 0.05 db/km (Ref. 1550nm)
Mode Field Diameter @1310nm	9.3 µm +/- 0.5
Mode Field Diameter @1550nm	10.5 (typical)
Typical Core Diameter	8.3 µm
Zero Dispersion Wavelength	1300nm <= $?_0$<= 1324nm
Dispersion coefficient at 1550nm	18 ps/nm*km
Dispersion coefficient @ 1310nm	<= 3.2 ps/nm*km
Zero Dispersion Slope @ $?_0$	S_0 <= 0.092 ps/km*nm^2
PMD for cabled fiber	N/A

4.3 Dispersion Shifted Single-mode Fibers Optical Specifications

4.3.1 Corning SMF/DS CPC3 (Issued: 7/92)

Attenuation @ 1300nm (dB/km)	<= 0.5 (typical)
Attenuation @ 1550nm (dB/km)	<= 0.25
Attenuation vs Wavelength: 1525-1575nm	Max difference 0.05 db/km (ref. 1550nm)
Mode Field Diameter @1550nm	8.1 +/- 0.65 µm
Typical Core Diameter	8.2 µm
Zero Dispersion Wavelength	1535nm <= $?_0$<= 1565nm
Zero Dispersion Slope	S_0 <= 0.085 ps/km*nm^2
Total Dispersion (ps/nm*km)	<= 2.7 over the range 1525 to 1575nm
PMD Link Value	<= 0.1 ps/vkm

Dispersion Calculation:

$D(?) = S_0*(? – ?_0)$[ps/nm*km], for 1500nm <= ? <= 1600nm

4.3.2 Pirelli (FOS) SM-DS Cat.A – G.653 compliant

Attenuation @ 1310nm (dB/km)	<= 0.39
Attenuation @ 1550nm (dB/km)	<= 0.20
Attenuation vs Wavelength: 1525-1575nm	Max difference 0.05 db/km (ref. 1550nm)

Mode Field Diameter @1550nm	8.1 +/- 0.65 µm
Zero Dispersion Wavelength	1535nm <= ?$_0$<= 1565nm
Zero Dispersion Slope	S_0 <= 0.085 ps/km*nm^2
Total Dispersion (ps/nm*km)	<= 2.7 over the range 1525 to 1575nm
PMD Link Value	N/A

Note: This fiber is fabricated with Corning "Outside Vapor Deposition" (OVD) technique. This could be one reason why the parameters' values are very close to the Corning SMF/DS.

4.4 Non-Zero Dispersion Shifted Single-mode Fibers Optical Specifications

This is the fiber category optimized for DWDM. There are a variety of fibers available. The reason we have such a variety of fibers is that DWDM is rapidly evolving: channel density is increasing, channel bit rates are increasing, new bands are occupied and new amplification technologies are employed. This evolution poses new challenges to scale DWDM networks with the right fiber optics technologies. *Every fiber has its different design approaches to balance dispersion, nonlinear effects, channel spacing, channel power and laser chirp*. It is all about tradeoffs in the design of high-speed, high-channel-density, long-haul optical DWDM networks. The way these tradeoffs are addressed is not unique, hence in the NZDS class is probably the most crowded and most difficult to understand.

Let's review the major NZDS fibers made available in the 1990s.

4.4.1 The ATT/Lucent Truewave Family of NZDSF

The first generation of Truewave fiber was originally developed in 1993 by ATT. Since then, the Truewave family has evolved under the Lucent brand.

After the TW-AT&T, the next member of the family was named Truewave Classic (TW-C). In the data sheet below, we notice a slightly higher CD coefficient and a slightly reduced dispersion slope compared to the TW-AT&T.

Following the TW-C, Lucent introduced the Truewave Plus (TW+). Even in this case the CD properties have been modified. The rest of the optical parameters are left unchanged.

The Truewave evolution continued with the introduction of major changes in the Truewave Reduced Slope (TW-RS), which, according to Lucent, represent the largest part of installed Truewave. The TW-RS is characterized by a higher CD and shows a decrease of about 36% in the dispersion slope. These two properties translate in a performance improvement for high-density DWDM applications.

The latest member of Truewave family, the Truewave Reach, has been introduced in 2002. The TW Reach is a fiber optimized for application in the S, C and L band and for Raman assisted amplification. (The data sheet is currently not available).

Truewave AT&T (TW-AT&T) (1993)

Attenuation @ 1550nm (dB/km)	0.20 – 0.25 (customer specifies max value)
Attenuation vs Wavelength: 1525-1575nm	Max difference 0.05 db/km (ref. 1550nm)
Attenuation @ 1310nm (db/km)	0.4 (typical)

Attenuation @ water peak 1383 +/- 3nm	< 2.05 dB/km
Mode Field Diameter @1550nm	8.4 +/- 0.6 µm
Typical Core Diameter	6.0 µm (typical)
Effective Area @ 1550nm	52.1 (-4.3/11.2) $µm^2$
Dispersion between 1540 to 1565nm	1.0 <= |D|<= 4.0 ps/nm*km
Zero Dispersion Wavelength	**1515 +/-20 nm**
Dispersion @ 1550nm	**2.4 +/-1.5 nm**
Zero Dispersion Slope	**S_0 <= 0.095 ps/km*nm^2**
Dispersion Slope @ 1550nm	S_0 <= 0.069 ps/km*nm^2
Total Dispersion (ps/nm*km)	<= 2.7 over the range 1525 to 1575nm
PMD Individual Fiber	<= 0.5 ps/vkm

Truewave Classic – TW-C

Attenuation @ 1550nm (dB/km)	0.25
Mode Field Diameter @1550nm	8.4 +/- 0.6 µm
Effective Area @ 1550nm	52 $µm^2$
Zero Dispersion Wavelength	**1511 +/-17 nm**
Dispersion @ 1550nm	**2.7 +/-1.2 nm**
Dispersion Slope @ 1550nm	**S_0 <= 0.068 ps/km*nm^2**
PMD Individual Fiber	<= 0.5 ps/vkm

Truewave Plus –TW+

Attenuation @ 1550nm (dB/km)	0.25
Mode Field Diameter @1550nm	8.4 +/- 0.6 µm
Effective Area @ 1550nm	52 $µm^2$
Zero Dispersion Wavelength	**1597 +/-15 nm**
Dispersion @ 1550nm	**3.7 +/-1.0 nm**
Dispersion Slope @ 1550nm	**S_0 <= 0.068 ps/km*nm^2**
PMD Individual Fiber	<= 0.5 ps/vkm

Lucent Truewave RS (Reduced Slope) – G.655 compliant

The Truewave RS, introduced in 2000, represents an evolution of the original Truewave fiber. The main differences from the original Truewave are:

- Reduced dispersion slope for a more uniform chromatic dispersion across the C and L band. (~ 36% less variability).

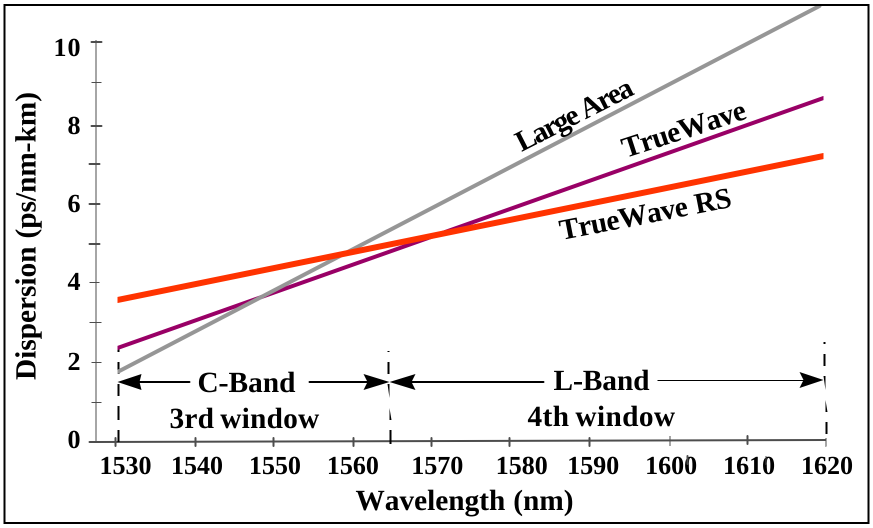

Figure 9, Dispersion slopes of TW, TW RS and a generic Large Effective Area Fiber

A reduced slope also allows a higher minimum dispersion thus better suppressing FWM.

- Engineered for the L-band (1565-1620nm).
- Reduced PMD.

Attenuation @ 1550nm (dB/km)	<=0.24
Attenuation @ 1625nm (dB/km)	<= 0.3
Attenuation @ 1310nm (dB/km)	<=0.4
Attenuation vs Wavelength: 1525-1625nm	Max difference 0.05 db/km (ref. 1550nm)
Attenuation @ 1310nm (db/km)	0.4 (typical)
Attenuation @ water peak 1383 +/- 3nm	< 1.0 dB/km
Mode Field Diameter @1550nm	8.4 +/- 0.6 µm
Mode Field Diameter @1550nm	8.7 +/- 0.6 µm
Dispersion C-band	2.6 <= |D|<= 6.0 ps/nm*km
Dispersion L-band	4.0 <= |D|<= 8.9 ps/nm*km

Zero Dispersion Slope @ 1550nm	S_0 <= 0.05 ps/km*nm^2
Dispersion 1310nm	-8/-9 ps/nm*km
PMD Individual Fiber	<= 0.05 ps/√km (tyical)
PMD Link Value	<= 0.1 ps/√km

4.4.2 Pirelli NZDSF Family

Freelight – G.655 compliant

The Freelight is the long haul, NZDSF currently produced by Pirelli. Of particular interest is that the data sheet reports the Effective Area. The value is similar to the LEAF fibers from Corning and we can classify the Freelight as a Large Effective Area fiber. (Typical Effective Areas range between 50 and 80µm. The smaller the area, the higher the nonlinear effects.) No mention is made of the dispersion slope, which is actually one of the key parameters distinguishing NZDSFs.

Attenuation @ 1550nm (dB/km)	<=0.23
Attenuation @ 1625nm (dB/km)	<= 0.25
Attenuation vs Wavelength: 1525-1625nm	N/A
Attenuation @ 1310nm (db/km)	N/A
Attenuation @ water peak 1383 +/- 3nm	N/A
Mode Field Diameter @1550nm	9.6 +/- 0.4 µm
Typical Effective Area	**72 µm^2**
Dispersion C-band	2.0 <= |D|<= 6.0 ps/nm*km
Dispersion L-band	4.5 <= |D|<= 11.2 ps/nm*km
Zero Dispersion Slope @ 1550nm	N/A
PMD	<= 0.1 ps/√km

Widelight – G.655 compliant

Pirelli positions the Widelight as their NZDSF for metro and "medium distance applications". The interesting thing is that the fiber has a negative dispersion characteristic and this is the same design approach adopted by Corning for their MetroCor NZDF. (A detailed explanation of the effects of negative chromatic dispersion on signal propagation is given later when discussing the Corning MetroCor).

Attenuation @ 1550nm (dB/km)	<=0.23
Attenuation @ 1625nm (dB/km)	<= 0.25
Attenuation vs Wavelength: 1525-1625nm	N/A
Attenuation @ 1310nm (db/km)	N/A
Attenuation @ water peak 1383 +/- 3nm	N/A
Mode Field Diameter @1550nm	8.1 +/- 0.5 µm

Typical Effective Area (@1550nm)	**50 μm^2**
Dispersion C-band	**-10 <= |D|<= -4.5 ps/nm*km**
Dispersion L-band	**-6.5 <= |D|<= -0.1 ps/nm*km**
Zero Dispersion Slope @ 1550nm	N/A
PMD	<= 0.2 ps/vkm

4.4.3 Corning NZDSF Fibers

Corning SMF-LS CPC6

Attenuation @ 1550nm (dB/km)	<= 0.25
Attenuation @ 1310nm (dB/km)	<= 0.5
Attenuation @ water peak 1383 +/- 3nm	< 2.0 dB/km
Attenuation vs Wavelength: 1525-1575nm	Max difference 0.05 db/km (ref. 1550nm)
Mode Field Diameter @1550nm	8.4 +/- 0.5µm
Mode Field Diameter @1310nm	6.6µm (typical)
Dispersion between 1530 and 1560nm	**-3.5 <= |D|<= -0.1 ps/nm*km**
PMD Link Value	<= 0.08 ps/vkm
PMD Individual Fiber	<= 0.2 ps/vkm

LEAF Family

LEAF stands for Large Effective Area Fiber. The approach Corning took to reduce all nonlinear effect (not just FWM and XPM) was to reduce the light intensity by increasing the Effective Area. In other words, the advantage is that the fiber can handle more power, therefore it reduces the regeneration costs in long haul applications. The idea, different from the Truewave family, carries some tradeoffs in the design. The most important tradeoff is that Large Effective Area fibers cannot maintain a low dispersion slope (see Fig. 8) and therefore a uniform dispersion across the whole C (or C+L) band.

Like the Truewave Family the LEAFs evolved through several generations.

There are three "generations" of LEAF fiber. The first generation is the original LEAF. In the latter part of 1998, Corning introduced enhancements made to this fiber, including an adjustment to the dispersion values (second generation). This was given the street name of "E-LEAF" by some in the industry, however Corning does not officially recognize the name.

In the first Quarter of 2001, Corning introduced enhancements to the PMD parameters. There were no changes to the chromatic dispersion values at this time (third generation). Thus, the only enhancements made to chromatic dispersion occurred in 1998.

Corning LEAF – First generation

Corning does not publish the full specification of the "old" LEAFs, but it disclosed the following information:

Dispersion between 1530nm and 1565nm	1.0 <= |D|<= 6.0 ps/nm*km
PMD Link Value (concatenated fibers)	<= 0.08 ps/√km
PMD Individual Fiber	<= 0.2 ps/√km

Corning LEAF – Second generation a.k.a. ELEAF

Dispersion between 1530nm and 1565nm	2.0 <= |D|<= 6.0 ps/nm*km
Dispersion between 1565nm and 1625nm	4.5 <= |D|<= 11.2 ps/nm*km
PMD Link Value	**<= 0.08 ps/√km**
PMD Individual Fiber	**<= 0.2 ps/√km**

Corning LEAF – Latest generation

Attenuation @ 1550nm (dB/km)	<= 0.25
Attenuation @ 1625nm (dB/km)	<= 0.25
Attenuation @ water peak 1383 +/- 3nm	< 1.0 dB/km
Attenuation vs Wavelength: 1525-1575nm	Max difference 0.05 db/km (ref. 1550nm)
Attenuation vs Wavelength: 1625nm	Max difference 0.05 db/km (ref. 1550nm)
Mode Field Diameter @1550nm	9.2 to 10 µm
Effective Area	**72 μm^2**
Dispersion between 1530nm and 1565nm	2.0 <= |D|<= 6.0 ps/nm*km
Dispersion between 1565nm and 1625nm	4.5 <= |D|<= 11.2 ps/nm*km
PMD Link Value (concatenated fibers)	<= 0.04 ps/√km
PMD Individual Fiber	<= 0.1 ps/√km

Corning MetroCor

The MetroCor fiber is a very interesting NZDS fiber, because it is characterized by a negative dispersion across the EDFA bands. This design allows increased reach of chirped or directly modulated laser sources. These low-cost sources are mainly used in metropolitan networks, hence the name MetroCor. Other fibers sharing the same principles are the Pirelli Widelight and the Corning SMF-LS.

What happens with directly modulated sources in the negative dispersion region, is that due to the interplay of laser chirp and the sign of the CD, the pulse undergoes an initial compression before spreading. The compression basically delays the beginning of the broadening of the signal, therefore it extends the reach of this type of sources.

On the other hand in positive dispersion regime, a directly modulated pulse spreads immediately without the initial compression.

And how do 10Gb/s sources behave in with negative CD? We need to distinguish:

- Externally modulated zero-chirp sources behave the same way in negative and positive dispersion regime, therefore they work well with this fiber.
- Pre-chirped sources, with a negative chirp, broaden without any compression, leading to poor performance on this fiber. These pre-chirped sources need a positive dispersion fiber to experience the benefit of an initial compression.

Attenuation @ 1310nm (dB/km)	<=0.50
Attenuation @ 1550nm (dB/km)	<=0.25
Attenuation @ 1605nm (dB/km)	<= 0.25
Attenuation vs Wavelength: 1525-1605nm	0.05 dB/km (ref. 1550)
Attenuation vs Wavelength: 1285-1330nm	0.05 dB/km (ref. 1550)
Attenuation @ water peak 1383 +/- 3nm	<= 0.4
Mode Field Diameter @1550nm	7.6 µm – 8.6µm
Dispersion between 1530nm and 1605nm	**-10 <= |D|<= -1 ps/nm*km**
Zero Dispersion Slope @ 1550nm	N/A
PMD Link Value	<= 0.1 ps/vkm
PMD Individual Fiber	<= 0.2 ps/vkm

4.4.4 Understanding the Positive and Negative Chromatic Dispersion Regime

We introduced the concept of positive and negative dispersion right after the MetroCor fiber, to help to understand why this fiber is optimized for directly modulated sources. The purpose of this section is to clarify the concepts of negative (D<0) and positive dispersion (D>0).

If we look at Fig. 3, 4 and 7 depicting the dispersion characteristics, we notice that, before the zero-dispersion wavelength, the CD coefficient is negative, whereas it is positive afterwards.

From a signal propagation standpoint what happens when D is positive and what happens when it is negative?

The following picture introduces the behavior of an un-chirped source in the presence of positive dispersion.

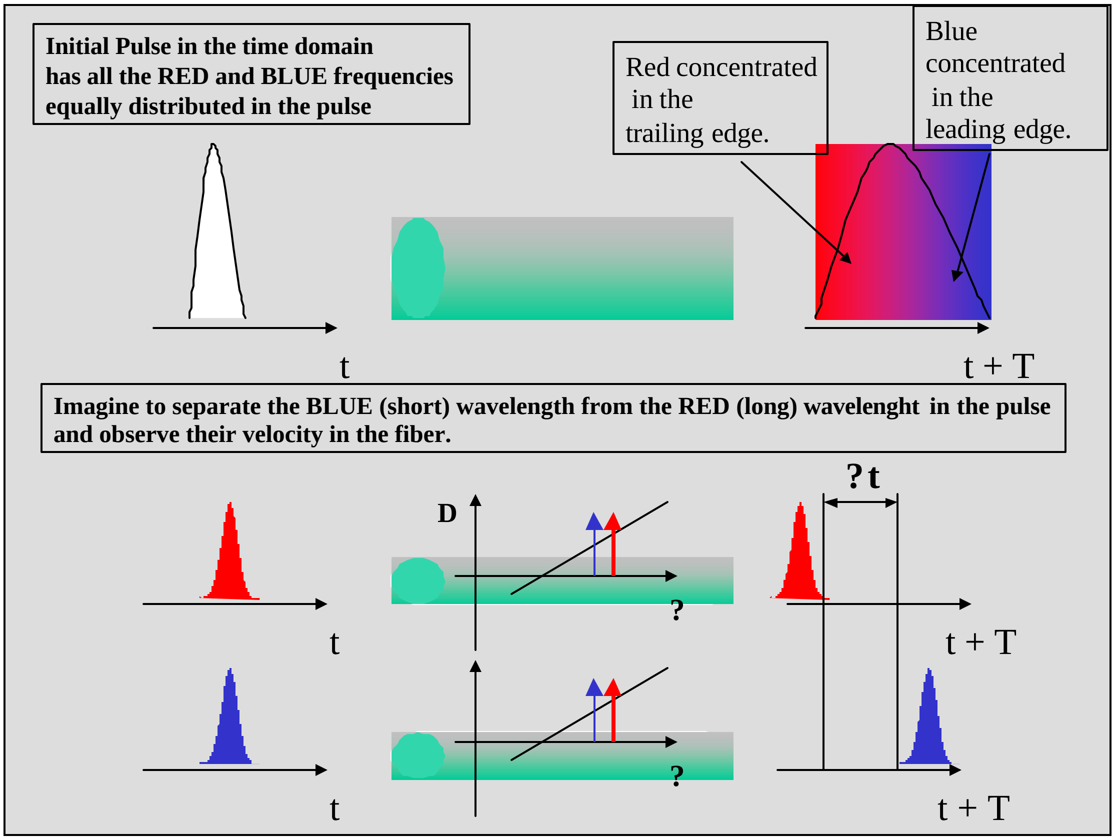

Figure 10, Positive dispersion fiber introduces a positive chirp in the optical pulse

In the positive dispersion regime (D>0), also called anomalous-dispersion regime, short wavelengths (BLUE) travel faster than short wavelengths (RED). In **Figure 10** Blue arrives ? t before Red.

This speed difference causes the pulse to spread.

Figure 10 also points out that while the pulse is traveling, a frequency shift (chirp) occurs within the pulse: *initially (in the white pulse) RED and BLUE components are equally distributed. After propagating through the fiber, at time t+T, the leading edge of the pulse has more BLUE components, whereas the trailing edge has more RED components.*

The fiber introduces chirp, or a frequency shift, in the leading and trailing edges of the pulse.

In negative dispersion (D<0), or normal-dispersion regime, the fiber introduces exactly the opposite chirp effects:

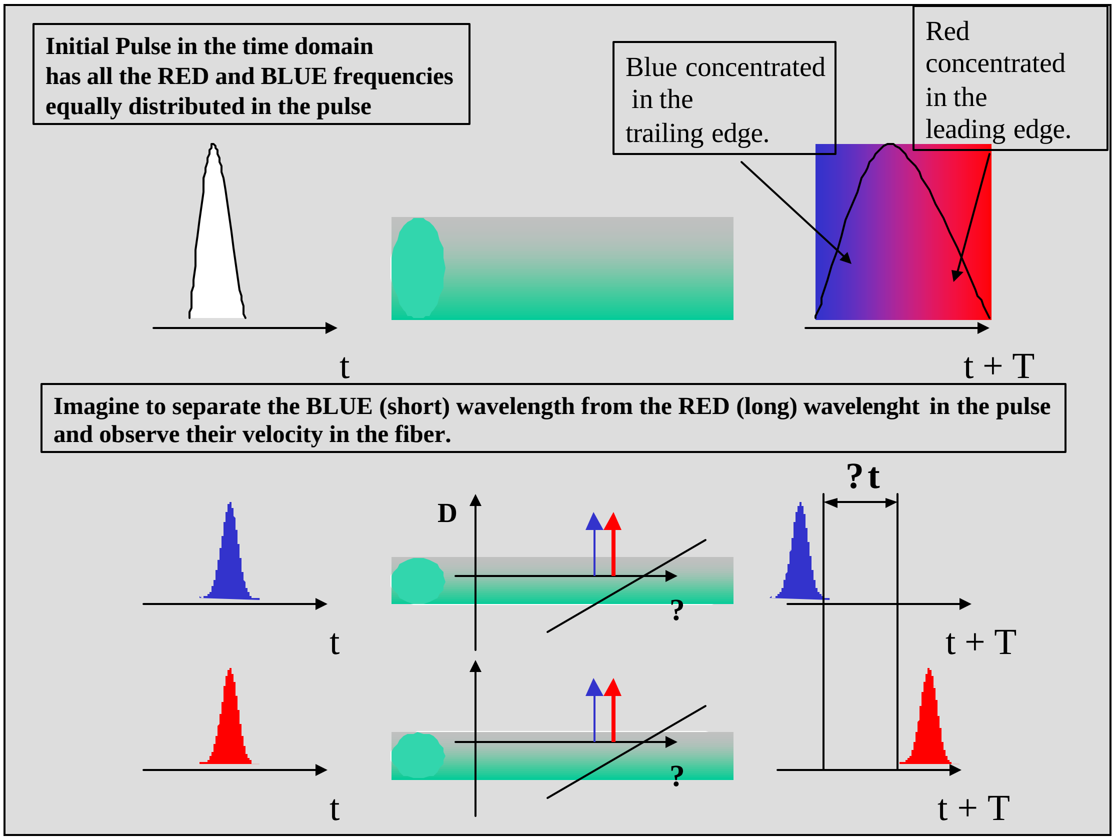

Figure 11, Negative dispersion fiber introduces a negative chirp in the optical pulse

In **Figure 11** the RED component travels faster than the BLUE one. (We can again observe a broadening effect caused by the speed mismatch). The aspect of Fig.10 we need to focus on, is the chirp introduced on the leading and trailing edge of the pulse. In this case the trailing edge has more BLUE components, on the other hand the leading edge has more RED components.

This is the critical point to understand fibers like the Corning MetroCor.

4.4.5 Chirped (directly modulated) optical pulses propagating in normal and anomalous dispersion regime.

We presented the MetroCor and the Pirelli Widelight as optimized for directly modulated lasers, typically employed in metropolitan applications. These fibers are characterized by a negative dispersion coefficient in the EDFA bands. What’s so peculiar about directly modulated sources?

A directly modulated source suffers a positive chirp effect, i.e. the leading edge of the pulse tends to shift towards the BLUE while the trailing edge towards the RED.

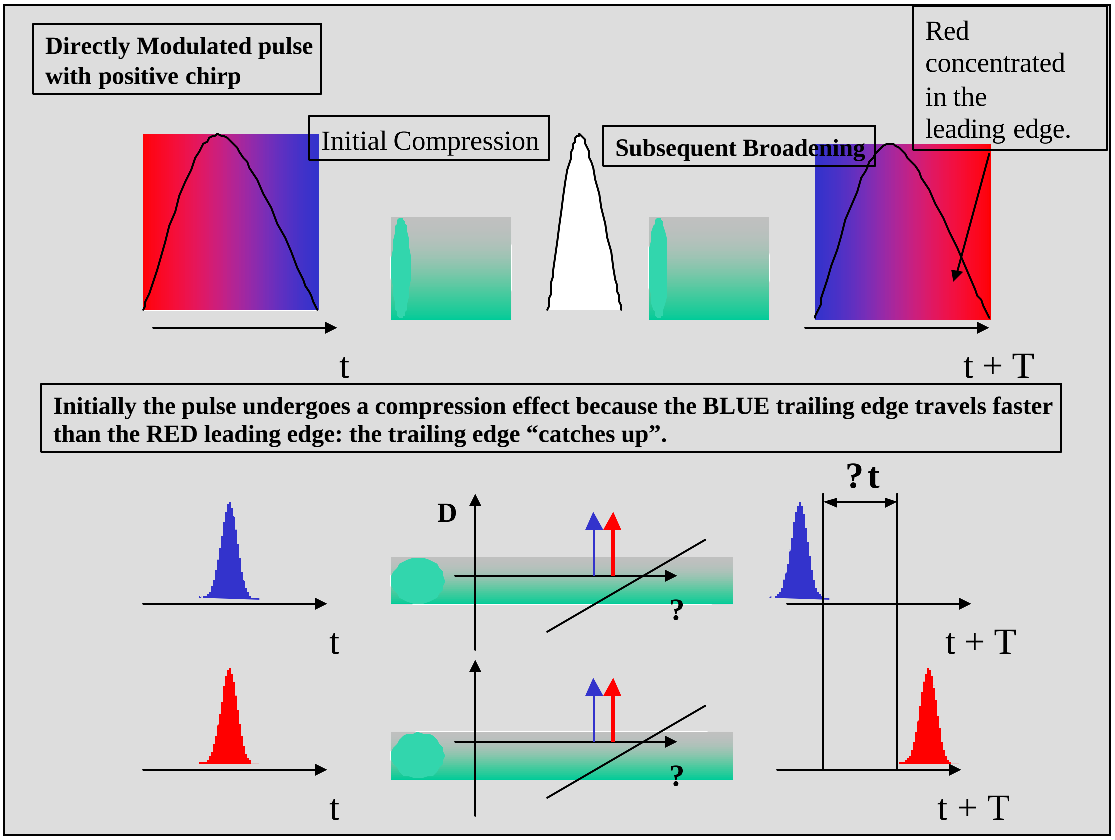

Figure 12, A positive-chirp pulse in negative dispersion (D<0) undergoes an initial compression and a subsequent broadening.

The negative chirp induced by the fiber in the normal-dispersion regime balances the positive chirp of the pulse. As a result, the RED trailing edge initially "catches up" with the BLUE leading edge and produces a compression of the pulse. After the maximum compression (white pulse), the pulse broadens again as explained in **Figure 10**.

With more common positive dispersion fibers, the positive chirp of the source and the fiber-induced chirp add up, thus rapidly broadening the signal. This is why directly modulated sources experience higher dispersion effects on standard G.652 fibers.

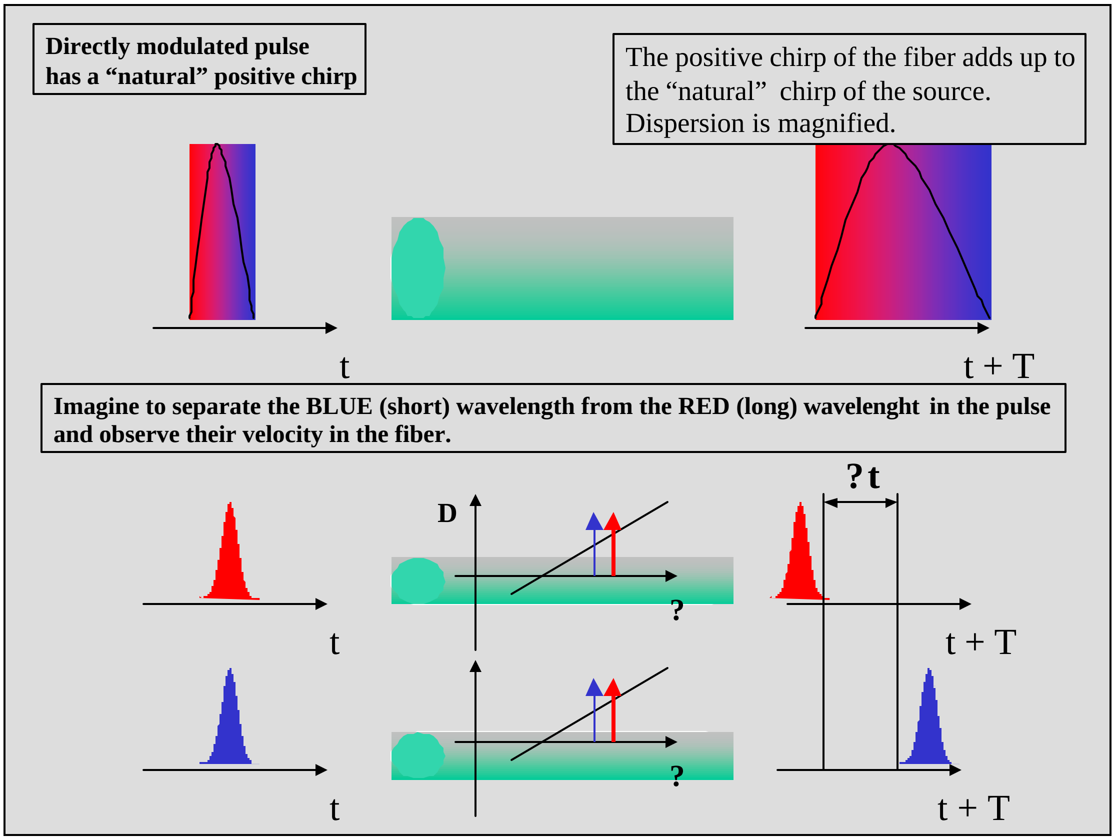

Figure 13, In anomalous-dispersion (D>0) regime the chirp of the source and the one induced by the fiber add up, augmenting the broadening of the pulse.

To summarize, in general, pulse broadening or pulse compression is determined by the combination of the dispersion sign and chirp sign of the laser. Identifying the characteristics of a source is therefore critical to understand dispersion effects.

- 2.5Gb/s directly modulated lasers are positive-chirp sources. They experience an initial compression in the normal-dispersion regime (D<0).
- Pre-chirped 10Gb/s lasers are usually negative chirp sources. They experience an initial compression in the anomalous-dispersion regime (D>0).
- Directly modulated or zero-chirp lasers behave the same way in negative and positive dispersion region.

4.4.6 Alcatel Teralight NZDSF Family

Alcatel 6910 Teralight- G.655 compliant

Attenuation @ 1550nm (dB/km)	<= 0.25
Attenuation @ 1620nm (dB/km)	<= 0.28
Attenuation @ water peak 1383 +/- 3nm	<= 1.5 dB/km

Attenuation vs Wavelength: 1525-1550nm	Max difference 0.03 db/km
Attenuation vs Wavelength: 1550-1575nm	Max difference 0.03 db/km
Attenuation vs Wavelength: 1550-1620nm	Max difference 0.05 db/km
Mode Field Diameter @1550nm	9.2 +/- 0.5µm
Effective Area	**63 μm^2 (typical)**
Dispersion @ 1440nm	D >= 0.1 ps/nm*km
Dispersion between 1530nm and 1565nm	5.5 <= D<= 10 ps/nm*km
Dispersion between 1565nm and 1620nm	7.5 <= D<= 13.8 ps/nm*km
Dispersion slope at 1550nm	**S_0 <= 0.058 ps/km*nm^2 (typical)**
PMD Link Value (concatenated fibers)	<= 0.08 ps/√km
PMD Individual Fiber	N/A

Alcatel 6912 Teralight Ultra - G.655 compliant

Attenuation @ 1550nm (dB/km)	<= 0.22
Attenuation @ 1625nm (dB/km)	<= 0.25
Attenuation @ 1450nm (dB/km)	<= 0.26
Attenuation @ water peak 1383 +/- 3nm	<=0.7 dB/km
Attenuation vs Wavelength: 1525-1550nm	Max difference 0.03 db/km
Attenuation vs Wavelength: 1550-1575nm	Max difference 0.03 db/km
Attenuation vs Wavelength: 1550-1625nm	Max difference 0.05 db/km
Attenuation vs Wavelength: 1440-1525nm	Max difference 0.1 db/km
Mode Field Diameter @1550nm	9.2 +/- 0.5µm
Effective Area	**63 μm^2 (typical)**
Dispersion @ 1440nm	D >= 0.1 ps/nm*km
Dispersion between 1530nm and 1565nm	5.5 <= D<= 10 ps/nm*km
Dispersion between 1565nm and 1625nm	7.5 <= D<= 13.4 ps/nm*km
Dispersion slope at 1550nm	**S_0 <= 0.052 ps/km*nm^2 (typical)**
PMD Link Value (concatenated fibers)	<= 0.04 ps/√km
PMD Individual Fiber	N/A

Alcatel 6911 Teralight Metro - G.655 compliant

Attenuation @ 1550nm (dB/km)	<= 0.25
Attenuation @ 1625nm (dB/km)	<= 0.28
Attenuation @ 1310nm (dB/km)	<= 0.4
Attenuation @ water peak 1383 +/- 3nm	<=1.0 dB/km
Attenuation vs Wavelength: 1525-1550nm	Max difference 0.03 db/km
Attenuation vs Wavelength: 1550-1575nm	Max difference 0.03 db/km
Attenuation vs Wavelength: 1550-1625nm	Max difference 0.05 db/km
Attenuation vs Wavelength: 1285-1310nm	Max difference 0.05 db/km
Attenuation vs Wavelength: 1310-1330nm	Max difference 0.05 db/km
Mode Field Diameter @1550nm	9.2 +/- 0.5µm
Effective Area	**63 μm^2 (typical)**
Dispersion @ 1440nm	D >= 0.1 ps/nm*km
Dispersion between 1530nm and 1565nm	5.5 <= D<= 10 ps/nm*km
Dispersion between 1565nm and 1625nm	7.5 <= D<= 13.4 ps/nm*km
Dispersion between 1285nm and 1330nm	-10 <= D<= -3 ps/nm*km
Dispersion slope at 1550nm	**S_0 <= 0.052 ps/km*nm^2 (typical)**
PMD Link Value (concatenated fibers)	<= 0.08 ps/√km
PMD Individual Fiber	N/A

4.5 Extended Band Single-mode Fibers Optical Specifications

This class of fibers is built with new manufacturing processes able to remove the OH ions into the fiber. These fibers virtually remove the water peak at around 1383nm, opening a continuous band from 1280nm to 1625nm. This is particularly desirable for Coarse Wavelength Division Multiplexing.

4.5.1 Lucent AllWave

Attenuation @ 1310nm (dB/km)	<=0.34-0.39
Attenuation @ 1385nm (dB/km)	<=0.31
Attenuation @ 1550nm (dB/km)	<=0.19-0.23
Attenuation @ water peak 1383 +/- 3nm	**<=0.31 dB/km**
Attenuation vs Wavelength: 1285-1330nm	Max difference 0.05 db/km (Ref. 1310nm)
Attenuation vs Wavelength: 1525-1575nm	Max difference 0.05 db/km (Ref. 1550nm)

Mode Field Diameter @1310nm	9.2 +/- 0.4µm
Mode Field Diameter @1550nm	10.5 +/- 1.0µm
Effective Area	80 μm^2
Zero Dispersion Wavelength	1300nm<= D >= 1322nm
Dispersion slope at 1550nm	S_0 <= 0.092 $ps/km*nm^2$
PMD Link Value (concatenated fibers)	<= 0.1 ps/vkm
PMD Individual Fiber	<= 0.05 ps/vkm (typical)

4.5.2 Corning SMF-28e – G.652 compliant

Attenuation @ 1310nm (dB/km)	Premium: <=0.34 Standard: <=0.35
Attenuation @ 1383nm (dB/km)	Premium: <=0.31 Standard: <=0.32
Attenuation @ 1550nm (dB/km)	Premium: <=0.20 Standard: <=0.22
Attenuation @ 1625nm (dB/km)	Premium: <=0.24Standard: <=0.24
Attenuation vs Wavelength: 1285-1330nm	Max difference 0.03 db/km (Ref. 1310nm)
Attenuation vs Wavelength: 1525-1575nm	Max difference 0.02 db/km (Ref. 1550nm)
Mode Field Diameter @1310nm	9.2 +/- 0.4µm
Mode Field Diameter @1550nm	10.4 +/- 0.8µm
Core Diameter	8.2µm
Zero Dispersion Wavelength	1302nm<= D >= 1322nm
Dispersion slope at 1550nm	S_0 <= 0.092 $ps/km*nm^2$
PMD Link Value (concatenated fibers)	<= 0.08ps/vkm
PMD Individual Fiber	<= 0.2 ps/vkm (typical)

4.5.3 Alcatel 6901 Enhanced Single Mode Fiber – G.652 compliant

Attenuation @ 1310nm (dB/km)	<= 0.34
Attenuation @ 1550nm (dB/km)	<= 0.21
Attenuation @ 1625nm (dB/km)	<= 0.24
Attenuation @ 1450nm (dB/km)	<= 0.25
Attenuation @ water peak 1383 +/- 3nm	<=0.33 dB/km
Attenuation vs Wavelength: 1285-1310nm	Max difference 0.035 db/km
Attenuation vs Wavelength: 1310-1330nm	Max difference 0.03 db/km
Attenuation vs Wavelength: 1525-1550nm	Max difference 0.03 db/km
Attenuation vs Wavelength: 1575-1550nm	Max difference 0.03 db/km
Mode Field Diameter @1310nm	9.0 +/- 0.4µm
Mode Field Diameter @1550nm	10.2 +/- 1.0µm

Zero Dispersion Wavelength	1310 +/- 10nm
Dispersion @ 1550nm	D =>17 ps/nm*km (typical)
Dispersion between 1285nm and 1330nm	D<= 2.7 ps/nm*km
Zero Dispersion slope	S_0 < 0.090 ps/km*nm^2
PMD Link Value (concatenated fibers)	<= 0.08 ps/√km
PMD Individual Fiber	N/A

4.6 Fiber Parameters Measured on common fiber types

Beside the specification supplied by the vendor, in the table we summarized the results of the measurements taken on real fibers. The recorded values can give an idea of the typical value of each parameter.

Fiber Type	D @ 1550 (ps/nm km)	S (ps/nm^{2}km)	D @ 1532.49 (ps/nm km)	D @ 1551.92 (ps/nm km)	D @ 1588.51 (ps/nm km)	?$_0$ (nm)	Effective area (μm^2)
SMF	17.1	0.06	16.1	17.2	19.4	1293	n/a
TW-RS	4.6	0.045	3.9	4.7	6.4	1446	55.8
FreeLight	4.313	0.0828	2.9	4.5	7.5	1498	72.2
TW +	4.0	0.063	2.9	4.1	6.4	1486	58.8
LEAF	4.13	0.106	2.3	4.3	8.2	1511	72.8
TW-C	3.5	0.065	2.4	3.6	6.0	1496	59.2
DS	0.1	0.074	-1.2	0.2	2.9	1549	48.3
LS	-1.6	0.074	-2.9	-1.4	1.3	1571	56.2

5 References

The collection of the fiber data sheets mentioned in this paper and the ITU-T G.65x recommendations can be found in compressed format at: http://metro-linux/paper_misc/fiber_collection.zip.

For the latest information on Lucent/OFS Fibers refer to: http://www.ofsoptics.com/product_info/ofs-fitel.shtml

For the latest information on Corning Fibers refer to: http://www.corning.com/opticalfiber/ (An account is required.)

For the latest information on Alcatel Fibers refer to: http://www.alcatel.com/opticalfiber/index.htm

For the latest information on Pirelli Fibers refer to:
http://www.pirelli.com/en_42/cables_systems/telecom/product_solutions/optical_fibres.jhtml

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