From Loss Test to Fiber Certification
Fiber Characterization Today
Part I: Chromatic Dispersion

White Paper

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When wavelength division multiplexing (WDM) was first introduced in 1996 to an eager marketplace fiber characterization was simple. Optical time domain reflectometer (OTDR) measurements and loss tests to verify the proper installation of the fiber link were all that was required. Only fiber attenuation, splice loss and optical return loss had to be tested.

In today's networks bit rates increase to 10 Gbit/s or 40 Gbit/s and beyond. The used bandwidth is extended from the C-band to the L- and S-band as well the channel spacing is reduced to as narrow as 12.5 GHz. Systems with 256 wavelengths and 10.2 Tb/s capacity [1] or 1.6 Tbit/s (40 * 42.7 bit/s) over 2000 km[2] are on their way.

In today's and tomorrow's networks the bandwidth potential of each fiber has to be tested and documented. There are many decisions to be made. Starting from fiber selection over the right choice for network equipment to dispersion management. Beside OTDR and loss test, which will remain mandatory measurements, chromatic dispersion (CD), first and second order polarization mode dispersion (PMD), polarization dependent loss (PDL), non-linear effects and wavelength dependent loss have to be taken into account for the link design today.

Understanding the different effects that limit the transmission bandwidth is the entrance to building profitable, high capacity networks. Also one has to know about the different measurement methods and compensation schemes to overcome the limitations. Part I will help to understand the issues related to chromatic dispersion.

Chromatic Dispersion is the variation in the speed of propagation of a light wave signal with wavelength [3]. It leads to spreading of the light pulses and eventually to inter-symbol-interference (ISI) with increased bit error rate (BER).

The origin of chromatic dispersion in single mode fibers as result from the interplay of material dispersion and wave-guide dispersion[4] this is shown in figure 1.

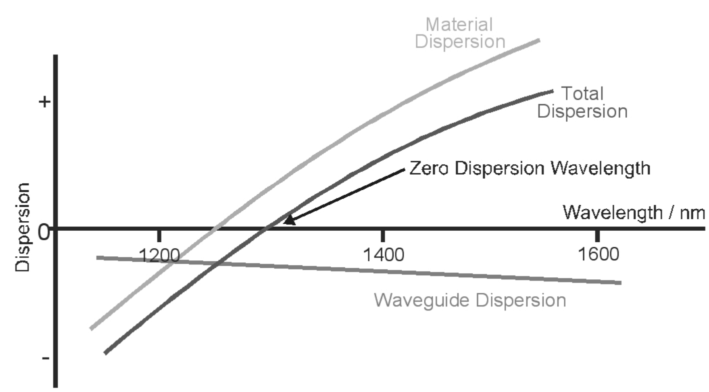

Figure 1: Total dispersion of a single mode fiber resulting from material- and wave-guide dispersion

The speed of light is dependent on the material that it travels in. Material dispersion describes the wavelength dependency of the refractive index. Wave-guide dispersion is due to the different mode field diameter of light in a single mode fiber at different wavelength.

A number of different fiber types have been developed in the past in order to extend the distance that signals can travel without chromatic dispersion compensation or to reduce the amount of chromatic dispersion compensation necessary. Figure 2 shows the dispersion of a Standard Single Mode Fiber (SSMF, ITU-G.652), a Dispersion Shifted Fiber (DSF, ITU-G.653), two different Non Zero Dispersion Shifted Fibers (NZDSF, ITU-G.655) and a Negative Dispersion Fiber (NDF, ITU-G.655). The standard single mode fiber is the single mode fiber that was first used. At this time transmission was carried out at 1310 nm. The dispersion-shifted fiber with zero dispersion at 1550 nm was introduced when transmission was carried out at 1550 nm and before wavelength division multiplexing (WDM) was considered. It made chromatic dispersion compensation unnecessary at 1550 nm. Later, when WDM was introduced, the reduced chromatic dispersion and the small effective area of the fiber led to significant non-linear effects. Different fiber types had to be developed with little but still sufficient chromatic dispersion and larger effective fiber core areas to mitigate non-linear effects. Negative Dispersion Fibers (NDF) show a negative chromatic dispersion in the wavelength range of interest. They are used for submarine applications where positive and negative dispersion fibers are used alternately [5]. For Metro applications, this fiber can be attractive especially when coupled with the interaction of positive chirp from many lasers [6], to build longer fiber links without chromatic dispersion compensation.

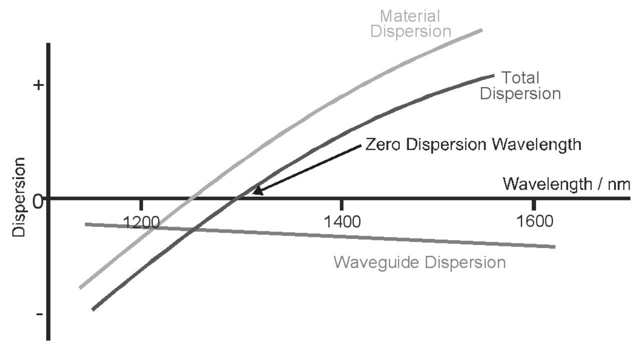

Figure 2: Chromatic dispersion of different common fiber types. SSMF: Standard Single Mode Fiber, NZDSF: Non Zero Dispersion Shifted Fiber, LEAF: Large Effective Area Fiber, DSF: Dispersion Shifted Fiber,
NDF: Negative Dispersion Fiber

In Table 1 typical dispersion and dispersion slope values for different fiber types are summarized.

Type of Fiber	**Typical Dispersion at 1550 nm**	**Typical Slope at 1550 nm**
SSMF ITU-G.652	17 ps/(nm km)	0.057 ps/(nm^2 km)
DSF ITU-G.653	0 ps/(nm km)	0.07 ps/(nm^2 km)
NZDSF ITU-G.655	2.6 to 8 ps/(nm km)	0.045 to 0.1 ps/(nm^2 km)
NDF (NZDSF) ITU-G.655	-8 to -3 ps/(nm km)	0.05 to 0.12 ps/(nm^2 km)

Table 1: Typical dispersion and dispersion slope values for different fiber types

As a figure of merit for the impact of chromatic dispersion on the systems signal quality, the tolerable dispersion for a certain power penalty is often specified. The dispersion-induced power penalty refers to the additional power required to maintain a certain bit error rate (BER) when dispersion is present, compared to the power required at the same BER when the link is dispersion-free.

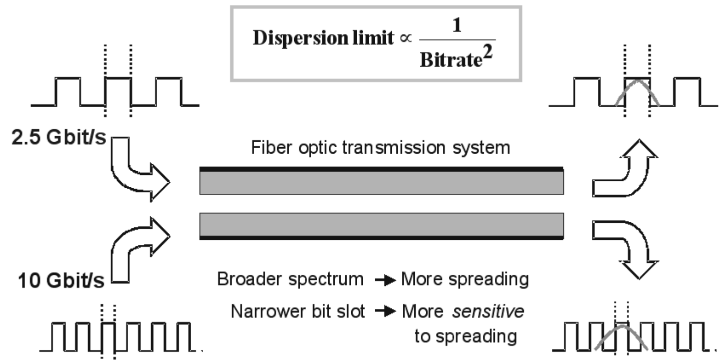

Figure 3: Bit rate dependency of the chromatic dispersion limit

Figure 3 illustrates the dispersion limit dependency on the bit rate. For low bit rates (e.g. 2.5 Gbit/s) the spectral width of the light pulses is small. Thus the spreading of the pulses is weak. Also the distance between two light pulses is large. This means that it needs a very long fiber link with high chromatic dispersion in order to make the pulses overlap. For higher bit rates this is different. On the one hand a 10 Gbit/s or 40 Gbit/s signal has a much broader bandwidth, so the pulse spreading is larger for the same amount of dispersion. On the other hand the light pulses are closer together so that the overlapping of the pulses starts with less spreading. The consequence of both effects combined is that the dispersion limit is inverse proportional to the square of the bit rate[7]. Chromatic dispersion is expressed as ps/nm where the ps refer to the pulse spreading and the nm refer to the spectral bandwidth of the signal that is dispersed.

Chromatic dispersion does not vary according to time and installation constrains. It is however temperature dependent. For dispersion shifted fibers the zero dispersion wavelength λ_0 varies +0.03 nm/K and for dispersion unshifted fibers +0.025 nm/K[3]. Typical values for the change of the dispersion coefficient D with temperature are between -0.0005 and -0.0038 ps/nm[8]. Chromatic dispersion is also sensitive to the signal itself. E.g. whether the signal has a NRZ (non return to zero) or RZ (return to zero) format. The type of modulation (direct or external modulation) plays also a role for the overall dispersion.

In table 2 the tolerable chromatic dispersion values for 1 dB power penalty at different bit rates are shown along with the corresponding fiber lengths. The examples are for a NZDS fiber with 4.4 ps/(nm km) and a SSM fiber with 17 ps/(nm km) for chirp-free transmission of NRZ signals at 1550 nm. As chromatic dispersion is directly proportional to the fiber length, chromatic dispersion of fibers is expressed in ps/(nm km).

Bit Rate	**SDH**	**SONET**	**Tolerable CD**	**Link length NZDSF**	**Link Length SSMF**
2.5 Gbit/s	STM-16	OC-48	16000 ps/nm	3640 km	940 km
10 Gbit/s	STM-64	OC-192	1000 ps/nm	230 km	60 km
40 Gbit/s	STM-256	OC-768	63 ps/nm	14 km	4 km

Table 2: Tolerable chromatic dispersion for 1 dB power penalty and corresponding fiber lengths

From table 2, it can be seen that for a bit rate of 2.5 Gbit/s chromatic dispersion is only problematic if the link length is long and the dispersion of the fiber is high. In contrast at 10 Gbit/s the maximum fiber length is 60 km and 4 km for a 40 Gbit/s signal respectively when a standard single mode fiber is used.

To build cost-effective, high capacity optical transmission networks dispersion management is one key factor. The right fiber type as well as the right dispersion compensation strategy has to be chosen. For short range or low bit rates SSM fiber is the most cost effective solution. If SSM fiber is used for long distances or high bit rates, dispersion compensation has to be done as well as the additional loss from the dispersion compensation modules (19 dB for a compensation of 180 km SSMF[9]) has to be taken into account. In order to build a long or high bit rate link with less dispersion compensation a NZDS fiber, which is 70 to 80% more expensive compared to SSM fibers,[9] can be used.

In many optical networks chromatic dispersion is compensated every 80 to 100 km[5].

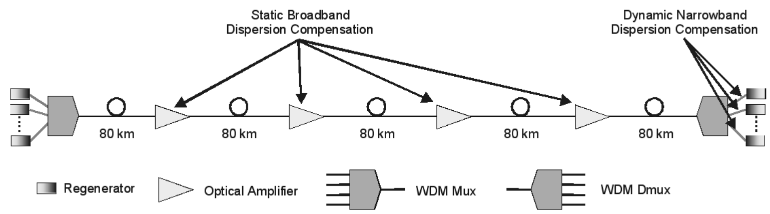

Figure 4: Dispersion compensation in optical networks

As shown in figure 4, broadband dispersion compensation is carried out at the amplifier stages statically, with dispersion compensating fibers (DCF) [10] or chirped fiber Bragg gratings [11]. When transmitting multiple channels in a wavelength band it is desirable to compensate all transmitted wavelength. This can be achieved with additional narrowband dispersion compensators. On the other hand, broadband dispersion - and dispersion slope compensation (dispersion slope match) is desirable. For DCF-based solution a slope match of 60% to 100% is available. A slope match less than 100% means that the outer channels are not fully dispersion compensated. High bit rate transmission is therefore limited to shorter fiber length for those wavelengths.

High-Order-Mode (HOM) dispersion compensating devices are one means of achieving a dispersion slope match of close to 100%[12]. The devices consist of two mode converters that convert the basic LP01 mode from the single mode fiber to a desired higher order mode and back again. A high order mode fiber with selected dispersion characteristics is placed between the mode converters. Beside dispersion slope match, the advantages of these devices are reduced losses compared to standard DC fiber and the lower sensitivity to non-linear effects[13].

For 40 Gbit/s signals in addition dynamic chromatic dispersion compensation will be optional when close to 100% dispersion slope match is achieved. This is to address the low dispersion tolerance [12] and to compensate the chromatic dispersion change due to fluctuations of systems operating conditions, e.g. temperature [14], as discussed above. These narrowband dispersion compensating linearly chirped or nonlinearly chirped fiber Bragg gratings have a spectral bandwidth of several nanometers [15].

Before compensating chromatic dispersion, the chromatic dispersion of a fiber network has to be measured. There are two main applications for measuring chromatic dispersion:

- Chromatic dispersion measurements to identify the fiber
- Precise determination of chromatic dispersion

Chromatic dispersion compensation can be done when the type of fiber is known. The dispersion-compensating module can be ordered to match the fiber that has to be compensated. Precise chromatic dispersion measurements are necessary if one has to account for the dispersion uncertainty due to fiber production or when a span of mixed fibers has to be measured.

Commonly used methods to measure chromatic dispersion are the:

- Modulated Phase Shift Method [16]
- Differential Phase Shift Method [17]
- Spectral Group Delay Measurement in the Time Domain (Time-Of-Flight) [18]

A schematic view of the modulated phase shift method is shown in figure 5.

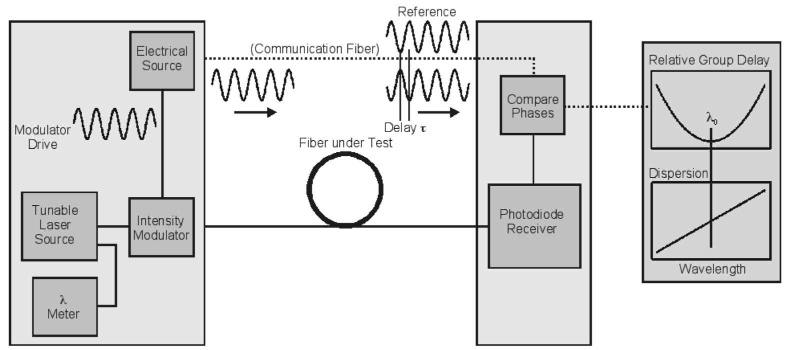

Figure 5: Schematic view of the modulated phase shift method

A tunable laser is intensity modulated. The signal is sent over the fiber under test, where a photodiode receives the signal. The phase of the modulated signal from the photodiode is compared to the reference phase of the electrical source. The phase measurement is repeated at intervals across the wavelength range of interest. From these measurements the relative group delay is known. A fitting function can be used to enhance the precision of the measurement. Commonly used fitting functions are a second order polynomial as well as the three-term and five-term Sellmeier functions[1]. From the derivation of the relative group delay the chromatic dispersion, the zero dispersion wavelength and the dispersion slope are calculated. The chromatic dispersion is given by:

$$D_\lambda = \frac{1}{L}\frac{\partial\tau}{\partial_\lambda}$$

D is the dispersion coefficient in ps/(nm km), τ is the relative group delay in ps, L is the fiber length in km and λ is the center wavelength in nm.

The zero dispersion wavelength λ_0 is at minimum group delay and at zero chromatic dispersion. Dispersion slope is simply the slope of the chromatic dispersion curve vs. wavelength.

In the set-up shown in figure 5, the tunable laser can be replaced by a broadband light source. The wavelength selection can than be done with a wavelength selective device e.g. a monochromator. This is typically done at the receiver side. The reference signal can also be generated at the receiver side to eliminate the need of a separate communication fiber.

1 Investigations have shown that a simplified 4-term fit can also be used [19]

The differential phase shift method is similar to the modulated phase shift method. The schematic view is shown in figure 6.

With this method the value of chromatic dispersion at a selected wavelength is determined directly from the measurement of the change of group delay across a small wavelength interval. A model equation can be fitted to the curve to improve the precision with which the zero dispersion wavelength, the dispersion coefficient and the dispersion slope can be determined. The chromatic dispersion is given by:

$$D_\lambda = \frac{\Delta\,\theta_\lambda}{360 \bullet f_m \bullet L \bullet \Delta_\lambda} \cdot 10^{12}$$

D is the dispersion in ps/nm/km, Dθ_λ is the measured phase change in degrees over the wavelength interval Δ_λ which is centered around the wavelength $\Delta\lambda$ and λ are given in nm). L is the fiber length in km and f_m the modulation frequency in Hz.

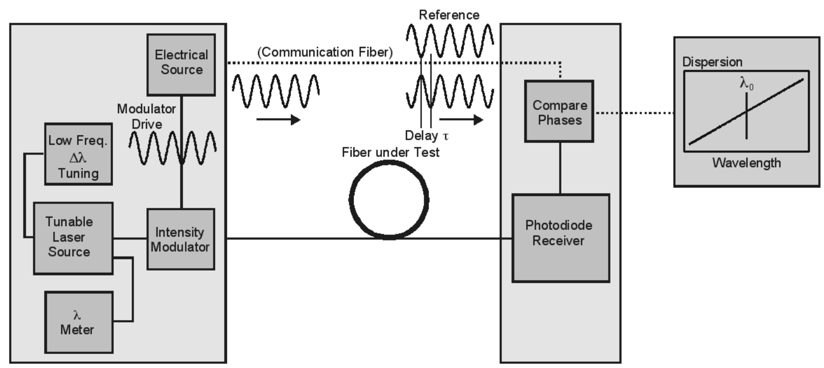

Figure 6: Schematic view of the differential phase shift method

The major difference compared to the modulated phase shift method is that in the differential phase shift method the phase is measured over a small wavelength interval and so the chromatic dispersion can be measured directly rather than measuring the relative group delay and calculate the derivation of it for determining the chromatic dispersion.

The spectral group delay measurement in the time domain also known as time-of-flight (TOF) is shown in figure 7. To take full advantage of this measurement method, it is preferably done single-ended with an optical time domain reflectometer (OTDR). Typical fiber spans of 100 km can be measured without connecting a reflective device (gold mirror) on the other end of the fiber, when the fiber termination is not an angled connector.

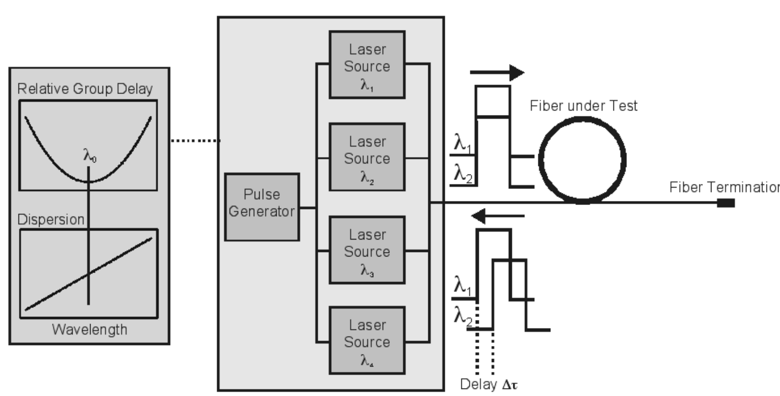

Figure 7: Spectral group delay measurement in the time domain method (time-of-flight)

Four or more wavelengths are pulsed by a pulse generator (e.g. an OTDR). The time delay of the pulses at each wavelength and thus the relative group delay is measured and the data is fitted with a fitting curve as in the case of using the modulated phase shift method. Commonly used wavelengths are in the range of 1310 nm to 1625 nm. From the relative group delay the dispersion coefficient, zero dispersion wavelength and dispersion slope are determined in the same way as with the modulated phase shift method.
Advantages and disadvantages of the different measurement methods are listed in table 3.

Measurement Method	Advantage	Disadvantage
Phase Shift	High accuracy Can measure over non-bi-directional components (e.g. Optical amplifiers)	Two instruments (source, receiver) needed Communication between source and receiver needed (some instruments) For full telecom wavelength range multiple light sources needed Fiber length measurement is not included in measurement High price
Time-Of-Flight	Measurement from one fiber-end possible Characterization of complete telecom wavelength range Link distance information included in the measurement Only one instrument needed Provides other measurement capabilities (Sources, OTDR) Low training effort/cost Low equipment cost	Cannot measure over non-bi-directional components (e.g. Optical amplifiers)

Table 3: Advantages and disadvantages of different chromatic dispersion measurement methods

For short fiber length in particular, i.e. for low dispersion values, the accuracy of the phase shift methods is higher when compared to the accuracy of the time-of-flight method. For all measurement methods the question arises how accurate one has to measure for high quality chromatic dispersion compensation. As discussed before dispersion compensation can be done by identifying the fiber type and by selecting a matching dispersion compensating module for exactly the fiber type and length. This is easily achieved with all the measurement methods available on the market. If the link is compensated taking into account the pure chromatic dispersion values, one has to consider the accuracy of the measurement itself and the accuracy of dispersion compensating modules. To give an example, a dispersion-compensating module for 80 km standard single mode fiber has a typical dispersion value of -1360 ps/nm ± 27 ps/nm at 1550 nm. The measurement accuracy obtained with different measurement methods is not overly different. A time-of-flight method would return a result of the fiber measurement with accuracy better than ± 15 ps/nm. Because the measurement itself and the uncertainty of the dispersion-compensating module are statistically independent, the overall accuracy of the link dispersion compensation is:

$$\Delta_{sum} = \pm \sqrt{(\Delta\text{compensation module})^2 + (\Delta\text{measurement})^2}$$

$$\Delta_{sum} = \pm \sqrt{(27\text{ps/pm})^2 + (15\text{ps/nm})^2} = \pm 30.9\text{ps/nm}$$

The uncertainty is therefore only ± 3.9 ps/nm, worsened due to the measurement uncertainty compared to the ± 27 ps/nm caused by the dispersion-compensating module itself. From this calculation, it can be seen that it is mainly the dispersion-compensating module that determines the uncertainty of the dispersion compensation.

In conclusion, when chromatic dispersion compensation can be made with standard dispersion compensating modules and measurements over optical amplifiers are not necessary the cost-effective time-of-flight measurement seems to be preferable over a more costly phase shift method based instruments.

[1] Y. Frignac et al., "Transmission of 256 wavelength-division and polarization-division-multiplexed channels at 42.7 Gb/s (10.2 Tb/s capacity) over 3x100 km of TeraLight fiber", OFC2002, FC5

[2] Zhu B. et al., "1.6 Tb/s (40*42.7 Gb/s) transmission over 2000 km of fiber with 100-km dispersion managed spans", ECOC2001, Vol. 6, pp. 16-17

[3] D. Derickson, Fiber Optic Test and Measurement, Prentice Hall, Inc., New Jersey

[4] Cohen, Leonard G., "Comparison of single mode fiber dispersion measurement" Journal of Lightwave Technology, 1985, LT-3 (5), pp. 958-966

[5] Y. Danziger et al., "Full-Band 40 Gb/s Lomg-Haul Transport Enabled by High-Order-Mode Dispersion Management", NFOEC 2000, Vol. 2, pp. 433-443

[6] C. Kennedy et al., "The performance of negative dispersion fiber at 10 Gbit/s and the significance of externally and direct modulated lasers", NFOEC 2001, Vol. 2, pp. 664-669

[7] R.M. Jopsen, " Measurement issues for dispersion compensation", Symposium on optical Fiber Measurements, SOFM 2000

[8] T. Kato et al., "Temperature dependence of chromatic dispersion in various types of optical fibers", Optics Letters 2000, Vol. 25, Iss 16, pp. 1156-1158

[9] J. Ryan, "Fiber considerations for metropolitan networks", Alcatel Telekommunications review, 1st Quarter 2002

[10] R. J. Nuyts et al., "Performance improvement of 10 Gbit/s standard fiber transmission systems by using the SPM effect in dispersion compensation fibers", IEEE Photn. Tech. Lett. 1996, Vol. 10, pp. 1406-1408.

[11] M.J. Cole et al., "Broadband dispersion-compensating chirped fiber bragg gratings in 10Gbit/s NRZ 110 km non-dispersion shifted fiber link operating at 1.55µm", Electron. Lett. 1997, Vol. 33, pp. 70-71

[12] M. Barratt, "Dispersion management for the next generation optical network", CDC 2001

[13] M. Tur et al., "Nonlinear properties of dispersion management modules employing high-order mode fibers", OFC 2001, TUS5

[14] A.E. Willner, "Nonlinearly chirped FBG for tunable chromatic dispersion compensation of multiple WDM channels", NFOEC 2001, Vol. 3, pp. 1595-1598

[15] G.E. Kohnke et al., "Fiber bragg gratings for dispersion compensation", OFC 2002, pp. 578-580

[16] EIA/TIA FOTP 169 measurement for SM fibers by the modulated phase shift method

[17] EIA/TIA FOTP 175 measurement for SM fibers by the differential phase shift method

[18] EIA/TIA FOTP 168 measurement for SM fibers by the spectral group delay measurement in the time domain method

[19] IEC 60793-1-42, Optical fibers-Part 1-42, Chromatic dispersion measurement methods

Notes

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