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Telecommunications Standards Advisory Committee (TSAC)

Next Generation National Broadband Network (NGNBN)

Optical Fibre Deployment

Part 1 – Fundamentals of Optical Fibre Communication

IMDA RD OFD - Part 1
Issue 1, 1 October 2016

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Acknowledgement

The Info-communications Media Development Authority (IMDA) and the Telecommunications Standards Advisory Committee (TSAC) would like to acknowledge the following members of the Technical Committee Working Group 1 (TSTC WG1) for their invaluable contributions to the preparation of this Reference Specification:

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In addition, IMDA would like to thank Mr Varghese Paulose, A*STAR/I^{2}R for his editorial contributions to this document.

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Contents

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Fundamentals of Optical Fibre Communication

1 Scope

The optical fibre is an optical waveguiding structure, and in this chapter, the basic principle behind the guiding of light in optical fibres is explained. Various attributes that are used to characterise the physical geometry and optical behaviour of optical fibres are also introduced. When an optical signal propagates along a fibre, it is affected by impairments due to attenuation, dispersion and non-linear effects. The origins of these impairments are explained and their influence on the signal integrity is also described.

2 Abbreviations

This Reference Specification uses the following abbreviations:

SMF	Single-mode Fibre
MMF	Multi-mode Fibre
MFD	Mode Field Diameter
CD	Chromatic Dispersion
PMD	Polarisation Mode Dispersion
DGD	Differential Group Delay
SRS	Stimulated Raman Scattering
SBS	Stimulated Brillouin Scattering
FWM	Four Wave Mixing
BER	Bit-Error-Ratio
BERT	Bit-Error-Ratio Tester
PRBS	Pseudorandom Bit Sequence
OSNR	Optical Signal to Noise Ratio
WDM	Wavelength Division Multiplexing

3 Principle of Guiding Light in an Optical Fibre

An optical fibre is a medium that guides a lightwave if the light ray meets the condition of total internal reflection. An optical fibre is made of a material that is transparent to the optical wave such as glass or plastic. As shown in Figure 1, the optical fibre consists of two parts: the core and the cladding, which guide a wave based on “total internal reflection”. The core is surrounded by the cladding, which has a lower refractive index.

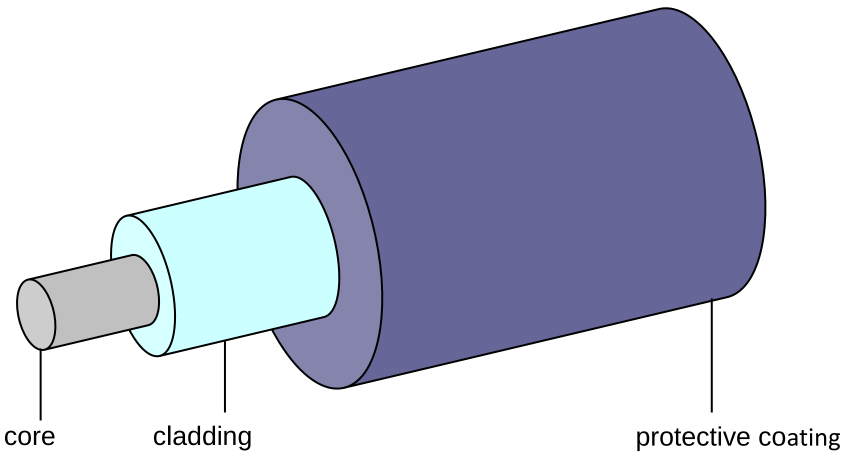

Figure 1: Structure of an Optical Fibre (not to scale)

Total internal reflection is the basic mechanism that governs the propagation of light in the optical fibre. To understand the principle of lightwave guiding, two well-known physical phenomena should be introduced: refraction and reflection.

3.1 Refraction

Refraction can occur when light propagates from one medium to another as shown in Figure 2. The lightwave changes its direction at the interface brought about by a difference in the refractive index of the two media, and this process can be explained using Snell’s law.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1} \tag{1.1}$$

where, the velocity of the light is also defined as follows:

$$v = \frac{c}{n} \tag{1.2}$$

(c is the velocity of light in vacuum and n is the refractive index)

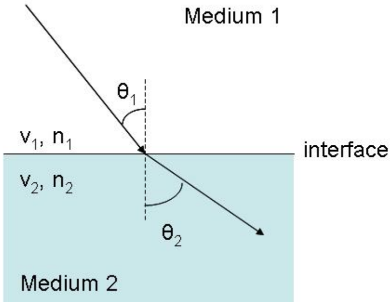

Figure 2: Refraction of Lightwave at the Interface of Two Different Media

3.2 Reflection

Reflection is the change in direction of a wavefront at an interface between two different media so that the wavefront returns to the medium from which it originated. The *law of reflection* is that the angle at which the wave is incident on the surface equals the angle at which it is reflected.

For refraction of light in the different medium, assuming that medium 1 has a much higher refractive index than that of medium 2 (n1 >> n2), there is a critical angle for the incident ray whereby θ_2 becomes equal to $\pi/2$ as shown in Figure 3 (a).

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \longrightarrow \qquad n_1 \sin\theta_c = n_2 \tag{1.3}$$

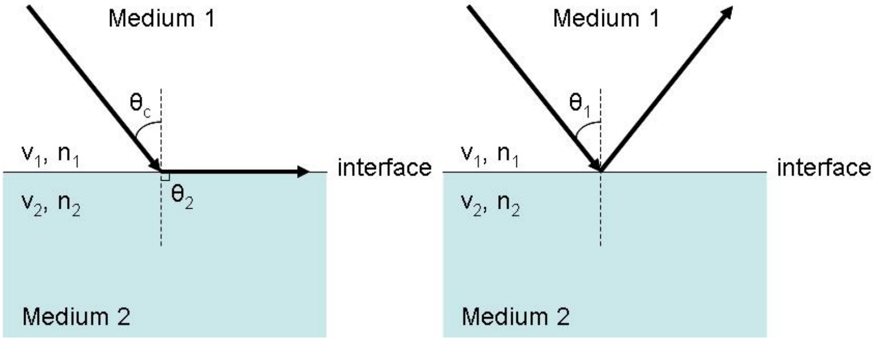

Figure 3 (a): Critical Angle Defined for $n_1 >> n_2$ and Figure 3 (b) Total Reflection for $\theta_1 > \theta_c$

For $\theta_1 > \theta_c$, the lightwave is completely reflected into the medium 1 once the incident angle is greater than the critical angle as illustrated in Figure 3(b). In an optical fibre, the lightwave remains inside the optical core once the rays meet the "$\theta_1 > \theta_c$" condition. Using the theory of total internal reflection, the propagation of light in a step index fibre can be explained (Figure 4).

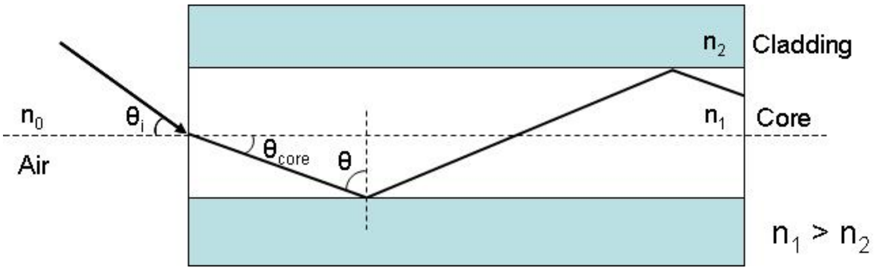

Figure 4: Rays in the Step Index Fibre

From Snell's law, the incident ray should meet the following conditions:

$$n_0 \sin\theta_i = n_1 \sin\theta_{core} \text{ or } \sin\theta_i = n_1 \sin\theta_{core} \tag{1.4}$$

where the refractive index of air n_0 is 1.

From trigonometry:

$$\sin\theta_{core} = \cos\theta = \sqrt{1 - \sin^2\theta} \tag{1.5}$$

To calculate the maximum ray angle of incident light, $\theta_{i,max}$, that can be guided by total internal reflection in the optical fibre, θ should meet the critical angle condition. Where it yields,

$$n_0 \sin\theta_{i,\max} = n_1 \sin\theta_{core} = n_1\sqrt{1-\sin^2\theta_c} \tag{1.6}$$

From (1.3)

$$n_0 \sin\theta_{i,\max} = n_1\sqrt{1-\sin^2\theta_c} = n_1\sqrt{1-\left(\frac{n_2}{n_1}\right)^2} = \sqrt{n_1^2-n_2^2} \tag{1.7}$$

For all rays that meet the condition, $\theta_i < \theta_{i,max}$, these rays satisfy the condition of total internal reflection of the optical fibre and they can propagate along the fibre with low power loss. The term $n_0\sin\theta_i$ is also known as the numerical aperture, and it represents the light-gathering capacity of the optical fibre.

3.3 Refractive Index

The refractive index is a measure of the change in the speed of light inside a medium (Eq. (1.2)). For instance, light travels at 0.71 times its speed in vacuum when it meets a medium that has a refractive index of 1.4.

The refractive index of some common materials is listed in Table 1. Note that the refractive index varies with temperature, pressure and the wavelength of the light.

Table 1. Refractive Index

Material	n
Vacuum	1
Air @ 0°C, 1 atmosphere	1.000293
Water @ 20°C	1.3330
Water ice	1.31
Diamond @ room temperature	2.419
Fused silica	1.458
Sapphire	1.762-1.778
Acetone	1.36
Teflon	1.35 – 1.38
Silicon	4.01

4 Single and Multi-mode Optical Fibres

Single-mode optical fibre (SMF) is the most common type of fibre deployed for high bandwidth communication where long length is required. On the contrary, the multi-mode fibre is associated with short distance and lower data rate communication. The term single-mode or multi-mode stems from the physical property of an optical fibre that allows the simultaneous propagation of multiple modes of light in the fibre. The multi-mode optical fibre can hold several light modes that are transmitted along different paths along the fibre. However, for the single-mode optical fibre, its physical structure is designed to propagate only one mode (path).

Table 2: Characteristics of Different Types of Optical Fibres

Type	Core Diameter	Cladding Diameter	Δ^*
Single-mode	8-10 µm	125 µm	0.1 ~ 0.2 %
Multi-mode	50 µm	125 µm	1 ~ 2 %
	62.5 µm	125 µm	1 ~ 2 %
	100 µm	140 µm	1 ~ 2 %

*Fractional index change at the core-cladding interface

4.1 Cut-off Wavelength

The cut-off wavelength is the minimum wavelength that will result in only one propagation mode in the fibre. A detailed definition of the cut-off wavelength can be found in EIA/TIA-455-170 [1].

4.2 Test Method for the Cut-off Wavelength (ANSI/TIA-455-80-C-2003) [2]

To measure the cut-off wavelength of the optical fibre, the transmitted power of the tested fibre is measured for wavelengths. In this case, the multi-mode fibre is used as a reference as it can support several modes. The attenuation difference (D(λ)) of the sample fibre is plotted against the wavelength used for testing. Here,

$$D(\lambda) = 10\log_{10}\frac{P_{SMF}(\lambda)}{P_{MMF}(\lambda)} \quad \text{dB} \tag{1.8}$$

As illustrated in Figure 5, the cut-off wavelength is determined by:

(a) Fitting the line of D(λ) for a longer wavelength slope.
(b) Drawing a 0.1 dB lower line parallel to the fitted line.
(c) The intersection point of the 0.1 dB lower line with the measured D(λ).

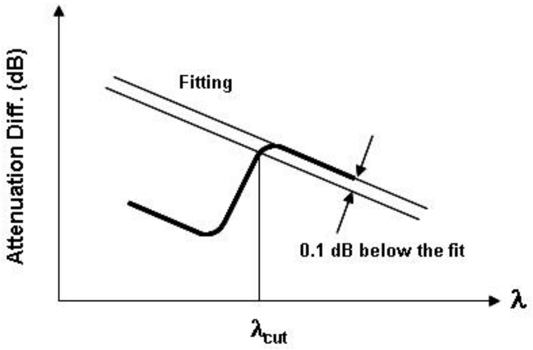

Figure 5: Plot for Cut-off Wavelength Measurement

5 Fibre Attributes

5.1 Fibre Geometry

The geometrical parameters of the fibre include cladding diameter, cladding non-circularity, core-cladding concentricity error and core non-circularity. These geometrical parameters are important when two fibres are to be matched.

- The **cladding diameter** is defined as the average diameter of the cladding.

- The **core diameter** is defined as the average diameter of the core.

- The **cladding non-circularity** is the difference between the largest radius and the smallest radius of the fibre divided by the average cladding radium, ellipticity. It is expressed as a percentage.

- The **core-cladding concentricity error** for a single-mode fibre is defined as the distance between the core and the cladding centres while it is defined as the distance between the core and the cladding centres divided by the core diameter for a multi-mode fibre. It is also expressed as a percentage.

- The **core non-circularity** is the difference between the largest and the smallest core radius divided by the core radius. The core non-circularity is measured only for a multi-mode fibre.

The definition of fibre geometry can be found in FOTP-176 [3] while test methods for measuring the geometrical characteristics of a fibre are provided in TIA-455-176-A [3] or IEC 60793-1-20 [4].

To measure these geometrical parameters, the input of the fibre is overfilled while the output is viewed via a video camera. For a high-resolution image, the image of the endface is magnified and digitised. The fibre’s coating at the ends are stripped and prepared with end angles less than 1˚ with near-perfect mirror surfaces.

The prepared fibre ends are set in the input and output stage of the measurement system shown in Figure 6. The system automatically adjusts the position to show the desired image. Then edge data on the cladding and the core are taken and fitted to the appropriate algorithms.

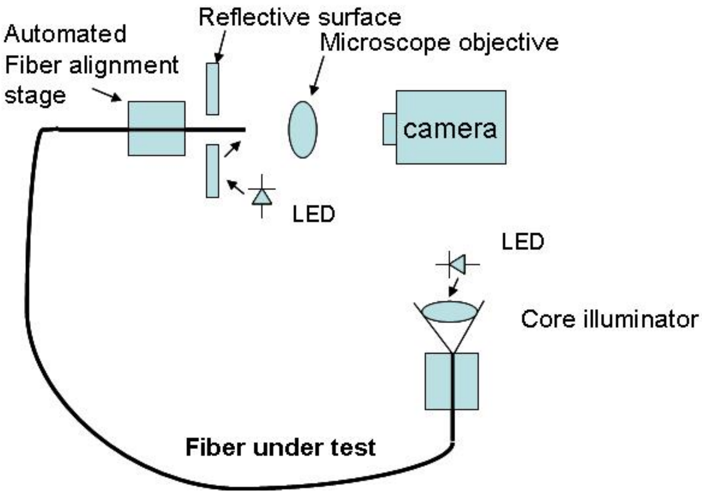

Figure 6: Set-up for Fibre Geometry Measurement

5.2 Mode-field Diameter

The mode-field diameter (MFD) is a measure of the beam width of the lightwave in the optical fibre. The power of the lightwave signal is mainly transmitted through the fibre core while a small portion of its power penetrates its cladding, as illustrated in Figure 7. In a single-mode optical fibre, MFD is mathematically defined as the diameter at which the optical power is reduced to $1/e^2$ of the maximum power. The MFD depends on the operating wavelengths; the shorter the wavelength, the smaller the MFD.

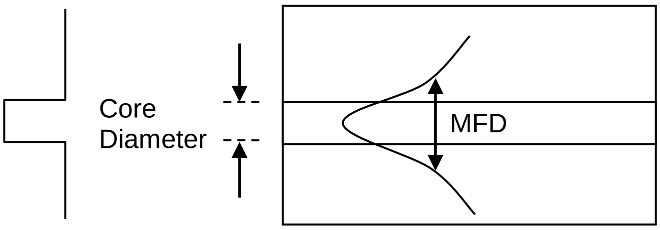

Figure 7: A Beam of Light Propagating in a Single-mode Fibre Has Most of Its Intensity in the Core and Partially in the Cladding

The measurement method for obtaining the mode-field diameter can be found in TIA/EIA-455-191-B [5] and FOTP-191 [5].

5.3 Minimum Bend Radius

The transmission of light is significantly affected by bends that occur in the fibre. If there is significant bending, optical attenuation losses in the fibre will increase. Optical fibre cable suppliers usually provide a parameter known as the minimum bend radius to specify the maximum amount of bending a fibre cable can tolerate without incurring too much attenuation loss. Chapter 2 provides a more detailed description on bending-related losses.

6 Propagation of Light in Fibres

6.1 Optical Power Attenuation

The propagation of light in an optical fibre can be numerically understood by solving Maxwell's equation. A mode of a fibre is a solution to Maxwell's equations that satisfies boundary conditions at the core-cladding interface. These modes suffer from losses due to the material absorption and the Rayleigh scattering in the fibre when the light propagates in the medium. The material absorption loss is caused by impurities in the fibre, but this has been significantly reduced as a result of advanced fibre manufacturing processes. Today, Rayleigh scattering is the major contributor to the attenuation losses in optical fibres.

Attenuation loss is an important factor limiting the transmission of a digital signal across long distances. Attenuation in a fibre can be quantified using the following equation:

$$\text{Attenuation (dB)} = 10 \log10 (\text{Output intensity /Input intensity}) \qquad (1.9)$$

An attenuation coefficient is always used to describe the fibre attenuation characteristics. The attenuation coefficient is the total loss in the fibre per kilometre, and usually has units of dB/km.

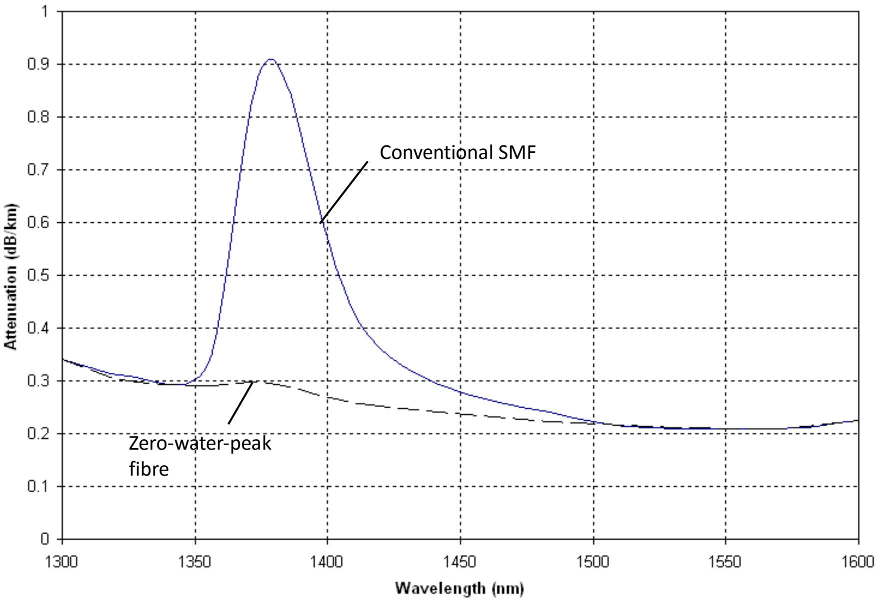

Figure 8: Attenuation Losses for a Single-mode Fibre

The typical losses are approximately 2.5, 0.3 and 0.2 dB/km at 0.8, 1.3 and 1.55 μm, respectively. In a single-mode fibre, the entire range of the wavelength that can be used for transmission is sub-divided into different bands, as shown in Table 3.

Table 3: ITU's Classification of Transmission Bands for Optical Fibre Communication

Band	Description	Wavelength
U band	Ultra-long wavelengths	1625 – 1675 nm
L band	Long wavelengths	1565 – 1625 nm
C band	Conventional	1530 – 1565 nm
S band	Short wavelengths	1460 – 1530 nm
E band	Extended	1360 – 1460 nm
O band	Original	1260 – 1360 nm

The second and third windows were originally separated by a “high attenuation peak” due to absorption caused by hydroxyl ions (OH) at around 1,400 nm. However, this peak can now be eliminated as a result of enhanced fibre manufacturing techniques. Sometimes, such fibres are known as “zero-water-peak” or “reduced-water-peak” fibres.

TIA-455-78-B describes the various methods for obtaining the attenuation of an optical fibre. There are four methods, namely the cut-back method, the insertion loss method, backscattering method and the spectral attenuation modelling method [6].

6.2 Dispersion in Fibres

6.2.1 Chromatic Dispersion (CD)

Ideally, the optical source used in the communication system should be a spectrally narrow source with zero spectral width. However, in practical systems, a significant portion of the source’s optical power is distributed across a non-negligible frequency band around the carrier frequency. Each spectral component that constitutes the overall optical signal travels along the fibre at a slightly different speed because of the wavelength-dependent nature of the refractive index (refer eq. 1.2). The result is that different spectral components arrive at the receiver at different times, thus distorting the waveform of the original signal. CD is present even in single-mode optical fibres because of the non-zero spectral width of the optical source.

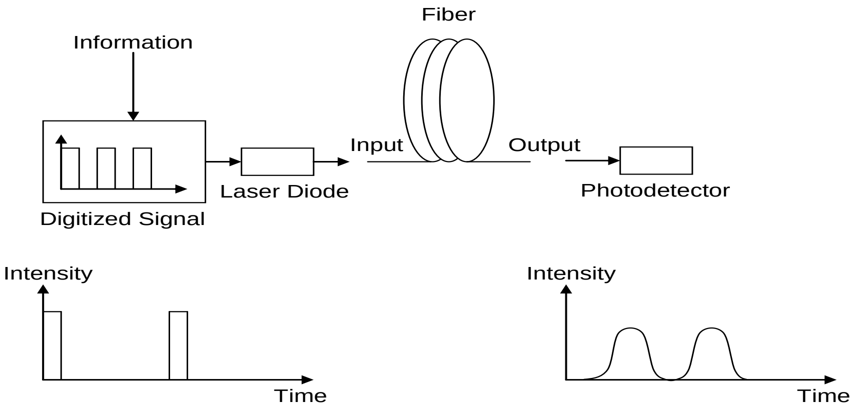

Figure 9: Illustrating the Effect of Chromatic Dispersion

TIA-455-175-B describes the various methods for obtaining the chromatic dispersion of an optical fibre. There are four methods: phase shift method, time-domain spectral group delay method, differential phase shift method and interferometry method [7].

6.2.2 Polarisation Mode Dispersion (PMD)

When a lightwave propagates in free space, it propagates as a transverse wave where the polarisation is perpendicular to the direction of the wave propagation. In this case, the fundamental mode has two orthogonal polarisations that travel at the same speed. However, when light propagates through optical fibres in reality, there are random fluctuations in the fibre’s circular symmetry that result in different propagation speeds for each polarisation component. The resulting speed difference between polarisation modes causes differential group delay $\Delta\tau = PMD_{coeff}\sqrt{L}$, where PMD_{coeff} is a coefficient measured in $ps/\sqrt{km}$ and L is the transmission distance in the optical fibre. In the fibre, PMD is statistically changed by time, wavelength, temperature and vibration.

PMD causes a time-domain spreading of the optical pulse. This kind of dispersion degrades the performance of the fibre-optic communication system. For a long fibre span, PMD has random characteristics since it is dependent on the birefringence along the fibre. Moreover, it is time dependent and is quite sensitive to temperature and mechanical vibrations. Therefore, expected values $<\Delta\tau>$ of the RMS pulse broadening ($\delta\tau$) or averaged differential group delay (DGD, $\Delta\tau$) among principal states of polarisation can be used for measuring PMD for the long fibre span.

The following are commonly used test methods for measuring the PMD coefficient:

a. PMD measurement for single-mode fibres by the Stokes parameter evaluation method (based on FOTP-122) [8]

In this testing method, results are obtained by Jones matrix measurement for the wavelength used for testing, regardless of fibre lengths and polarisation coupling. This is limited to single-mode operation only. The set-up consists of a tunable laser, polarisation controller, linear polarisers, a polarimeter and the fibre under test. The Stokes parameters are measured by the polarimeter while the polarisation controller is adjusted. Next, the differential group delay is calculated using these parameters and, with the DGD, the PMD coefficient can be computed.

b. PMD measurement for single-mode fibres by the interferometric method (based on FOTP-124) [9]

In this test method, the coherence time t_c of the source should be lower than the fibre's PMD values. The measurement set-up is considerably more complex compared to the Stokes parameter-based testing method. The fibre under test is placed within an interferometer set-up (Michelson or Mach-Zehnder) and, during the test, the path length of the interferometer is varied in a precise manner. This method provides a direct measurement of the averaged PMD coefficient as it measures $<\Delta\tau>$ or $<\Delta\tau^2>$ due to the interference of two lightwaves at the detector.

c. PMD measurement for single-mode fibres by the fixed analyser method (based on FOTP-113) [10]

This test method can be applied to both long- and short-length fibres, regardless of polarisation mode coupling. The test set-up consists of a broadband light source, a polariser, a polarised optical spectrum analyser and the fibre under test. The DGD is measured by analysing power level fluctuations in the optical spectrum.

6.3 Non-linear Effects

In an optical fibre system where there is high optical power or high bit-rate signals, the non-linearity effects in the fibre link should be considered. In this section, three of the most important non-linear effects are introduced: stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS) and four-wave mixing (FWM).

6.3.1 Stimulated Raman Scattering (SRS)

SRS is caused by the interaction between photons in the signal and the vibration of silica molecules in the fibre. This results in a scattering of light at a wavelength that is longer than that of the incident light as well as a transfer of power to the newly generated light. Some of the power from the incident light is also absorbed by the silica molecules in the fibre. The intensity of the scattered light increases exponentially once the incident optical power exceeds the threshold.

Generally, SRS is considered to be an undesirable non-linear effect because it is a performance-limiting factor in a multi-wavelength fibre transmission link, transferring energy from one wavelength channel to neighbouring ones. However, in some situations, this effect can be harnessed to provide amplification to a signal located at this longer wavelength. This is the principle behind the Raman amplifier.

6.3.2 Stimulated Brillouin Scattering (SBS)

While SRS is caused by scattering of light by the Silica molecules, SBS is caused by the electrostriction effect where the glass material undergoes compression in the presence of light. This effect produces an acoustic wave in the fibre and it propagates along the fibre together with the incident light. Due to the conservation of energy and momentum, a new optical signal known as a

Stokes wave is also produced. However, the Stokes wave travels in a direction that is opposite to the incident light and is thus detrimental to optical sources in a fibre transmission system.

SBS occurs in optical fibres at a lower input power compared with SRS. In other words, the threshold power for SBS is lower than SRS. However, once the threshold level is exceeded, most of the light is reflected back to the source. The Stokes wave is also generated at the lower frequency side of the input signal by an amount determined by the non-linear medium (Brillouin shift).

6.3.3 Four Wave Mixing (FWM)

The refractive index of silica is generally assumed to be power independent. However, for high input power, it is necessary to consider its power dependence. The refractive index changes depending on the input power and, for high input power, the influence of the higher order non-linearity component of the refractive index will become significant.

FWM is an interaction involving two or more optical signals occupying different wavelength channels in a fibre. Under certain conditions, when these optical signals become phase matched, they will interact, and new optical signals will be created at other wavelength channels. Through this process, energy from the original signals will be transferred to the new ones. Therefore, FWM has a detrimental effect in multi-wavelength channel systems because it creates crosstalk noise.

7 Types of Optical Fibres

The following table summarises the different types of fibres that are commonly used today.

Type of Fibre	Standard
Multi-mode fibre for 1300nm and 850nm wavebands (for short-reach applications)	ITU-T G.651 [11]
Standard single-mode fibre (most commonly deployed fibre for long-distance communication)	ITU-T G.652a and G.652b [12]
Non dispersion-shifted, single-mode fibre with reduced water peak (for multi-wavelength channels)	ITU-T G.652c [12]
Single-mode fibre with reduced water peak and low dispersion	ITU-T G.652d [12] *
Dispersion-shifted, single-mode fibre (zero dispersion wavelength shifted to 1550nm)	ITU-T G.653 [13]
Long distance undersea cable (higher power handling capability)	ITU-T G.654 [14]

* Fibres in Singapore's Next Generation NBN are based on ITU-T G.652d standard.

8 Important Performance Specifications for Optical Fibre Communication

8.1 Bit Error Ratio (BER)

Bit error ratio (BER) represents the error-ratio based on bit-by-bit counting. Since it is a statistical parameter, the measured value is dependent on the gating time, t, which corresponds to the time the data is collected and compared. Numerically it is defined as the number of errors counted divided by the total number of bits transmitted or received.

$$BER = \frac{E(t)}{N(t)} \quad (1.10)$$

where, *E(t)* is the number of bits received in error and *N(t)* is the number of total bits transmitted over time *t*. Generally BER is expressed as 10^{-xx}, i.e. BER of 10^{-6} means one error counted for a total of 1,000,000 bits transmitted.

To measure the BER of the system, the bit error ratio tester (BERT) is used. This comprises a pattern generator and an error detector. In the generator, the pseudorandom bit sequence (PRBS) pattern generator has the ability to change its pattern length from 2^7-1 to 2^{31}-1, and the signal levelling, so that end-users can modify the signal for their purpose. The following figure shows the general set-up for testing BER using BERT.

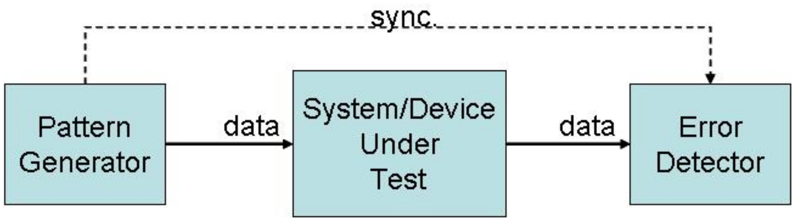

Figure 10: General BER Test Set-up

8.2 Eye Diagram

An eye diagram is an oscilloscope’s display of a repetitively sampled signal, and is a useful tool to observe and analyse the performance of binary digital (or analogue) signals. It can provide visual information to evaluate and troubleshoot digital transmission systems. The eye diagram is created by capturing the time-domain signals and then overlapping their traces on the display. Its name originates from the fact that the pattern looks like a human eye. Eye measurement provides insights on the waveform characteristics of digital signals such as rise time, overshooting, signal-to-noise and jitter.

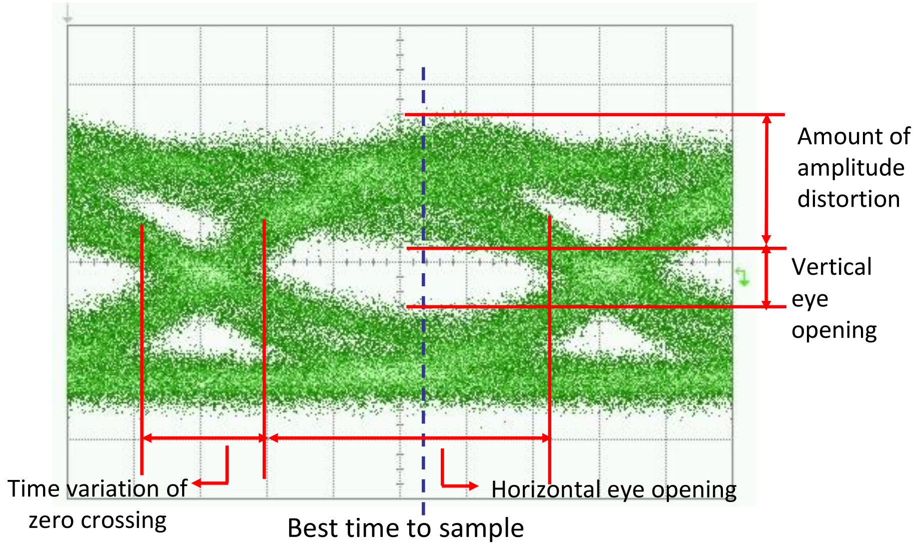

Figure 11: Measured Eye Diagram of a Digital Signal in an Optical-fibre Communication System

The above figure shows a measured eye diagram for a digital signal in an optical transmission system. The vertical eye opening indicates the amount of difference in signal level between the one-bits and the zero-bits. The bigger the difference, the easier it is to discriminate between ones and zeros. The part of the eye where the vertical opening is the largest represents the best time to sample the signal. The horizontal eye opening indicates the amount of jitter present in the signal. The wider the eye opening, the less jitter it is likely to possess. Thus, the amount of eye opening is an indication of the signal's quality, so the larger the eye opening, the easier it is for the signal to be detected without errors. When the eye is nearly closed, it is very difficult or impossible to derive correct data from the signal. The following figure shows a basic eye diagram measuring set-up.

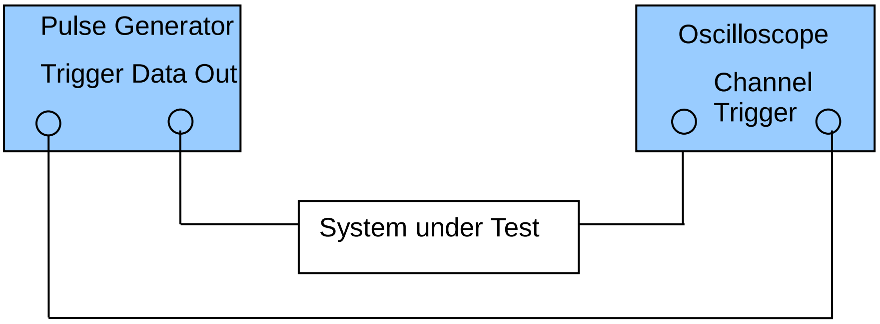

Figure 12: Eye Diagram Measurement Set-up

8.3 Optical Signal-to-Noise Ratio (OSNR)

The optical signal-to-noise ratio (OSNR) is widely used to estimate the performance of a Wavelength Division Multiplexing (WDM) optical transmission system. It is the key performance parameter for characterising the transmission performance of an optical signal and it can be used to estimate the BER at the receiver of a transmission link. OSNR is defined as the ratio of signal channel power to the noise power in an optical channel (within a specified optical bandwidth):

$$OSNR(dB) = 10 \cdot \log_{10}\left(\frac{S}{N}\right) \quad (1.10)$$

where, *S* represents the optical signal power and *N* is the average optical noise power in the signal channel.

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Annex

Corrigendum / Addendum

Changes to IDA RD OFD - Part 1 Issue 1 Rev 1, May 2011			
Page	**RS Ref**	**Items Changed**	**Date of Issue**
		The IDA RD OFD - Part 1 Issue 1 Rev 1 (May 2011) has been re-issued as the IMDA RD OFD - Part 1 Issue 1 (Oct 2016)	1 Oct 2016

Changes to IDA RD OFD - Part 1 Issue 1, Jul 10			
Page	**RS Ref.**	**Items Changed**	**Effective Date**
—	—	Change of IDA's address at cover page to Mapletree Business City.	1 May 11