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New Development in Fiber Technologies

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ABSTRACT

Optical fiber technologies has gone through tremendous developments since its first installation in the 1970s. Three decades later it has become the backbone of the global telecommunications network, providing high speed internet access to homes and offices, and instant communications through telephones all around the world. In present day internet service provider, cable television providers, telephone providers and power providers has established their own fiber optic network. Compared to copper wires, fiber optics are immune to electromagnetic interference and its low attenuation while maintaining high bandwidth over long distances. These features makes fiber optics quite popular in the telecommunication business, which at this moment is a billion dollar industry. In order for various fiber optics manufacturer to develop compatible fiber optics systems, ITU Telecommunication Standardization Sector(ITU-T) have developed several fiber optics standards.

Optical fibers are not only for a mainstream telecommunications market, other fibers have been developed for specific purposes, so-called non-standard specialty fibers. There's a rapidly growing need for these non-standard fibers in the niche market. These fibers have their properties altered, for example special coatings around the fiber that help withstand high temperatures.

The thesis will give a brief overview of the characteristics of both optical fiber standards and non-standard, and a comparison of the standard fibers based on their similar purposes.

The work done by standard organization such as the ITU-T, have helped evolve this fast changing telcommunications industry. Their work has helped with defining the technology and architecture of the fiber optical transport system. Development of the standard gives a technical specification giving shape to the global telecommunications infrastructure.

The non-standard optical fiber, which was ones a boutique business in 1990s, quickly rose to a $239 million market. Following the dynamic market growth, it grew further to $635

million in 2010 and $673 million, and is expected to reach almost a billion dollar industry by the year 2016. Its rapid growth shows that the non-standard fiber industry has had a tremendous development, but is still not comparable to the standard fiber market.

SAMMENDRAG

Optisk fiber har vært gjennom en utrolig utvikling siden det var først installert i 1970 tallet. Tre tiår senere har den blitt ryggraden for the globale telekommunikasjons nettverket, forsynet høy hastighet internett tilgang til hjem og kontorer, og instantan kommunikasjon gjennom telefon over hele verden. I dag har internettleverandører, telefonleverandører, TV-leverandører og strømleverandører har etablert sitt eget fiberoptisk nettverk. Sammenlignet med kobberkabler, er optisk fiber immun mot elektromagnetisk interferens and har lav demping mens det har høy båndbreddet over lange distanser. disse egenskapene gjør fiberoptikk svært populær i telekommunikasjons industrien, som for øyeblikket er et milliard dollar industri. For at ulike fiberoptiske produsenter skal kunne utvikle kompatible fiberoptiske systemer, har "ITU Telecommunication Standardization Sector(ITU-T)" utviklet noen fiberoptiske standarder.

Optisk fiber er ikke bare for konvensjonell telekommunikasjons markedet, andre fiberoptikk har blitt utviklet for spesielle formål, såkalte ikke-standard spesial fiber. Det er et voldsomt behov for slike ikke-standard fiber i det nisje markedet. Disse fibere har fått egenskapene forandret, foreksempel spesial belegg som omringer rundt fiberet som hjelper det til å motstå høye temperaturer.

Avhandlingen vil gi en kort oversikt over karakteristikken til det optiske fiberets standard og ikke-standard, og en sammenligning mellom standardene basert rundt deres lignende formåler.

Arbeidet gjort av standard organisasjoner som ITU-T, har vært med å hjelpe utviklingen til dette hurtig voksende telekommunikasjons industrien. Deres arbeid har hjelpet med å definere teknologien og arkitekturen til det fiberoptiske transport systemet. Utviklingen av standarder gir tekniske spesifikasjoner for å gi grunn til det globale telekommunikasjonens infrastruktur.

De ikke-standard optiske fiber, som en gang var en butikk industri i 1990 tallet, vokste kjapt til et $239 million industri.

Med det dynamiske voksende markedet, vokste det videre til $635 millioner i 2010 og $673 millioner i 2011, og er forventet med å nå nesten et milliard dollar industri ved året 2016. dets hugtig vekst viser at det ikke-standard fiberoptiske industrien har hatt et voldsom utkvikling, men fremdeles er det ennå ikke sammenlignbar med det standard fiberoptiske markedet.

ACKNOWLEDGMENTS

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ACRONYMS

CD	Chromatic Dispersion
CPM	Cross Phase Modulation
CWDM	Coarse Wavelength Division Multiplexing
DGD	Differential Group Delays
DCF	Dispersion Compensated Fiber
DFF	Dispersion Flattened Fiber
DSF	Dispersion-Shifted Fiber
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
FBG	Fiber Bragg Gratings
FTTH	Fiber to the Home
FTTZ	Fiber to the Zone
FWM	Four Wave Mixing
ICT	Informations and Communication Technologies
IEC	International Electrotechnical Commission

ISO	International Standards Organization
ISP	Internet Service Provider
ITU-T	ITU Telecommunication Standardization Sector
LWP	Low Water Peak
MFD	Mode Field Diameter
NA	Numerical Aperture
NRZ	Non-Return-to-Zero
NZ-DSF	Non-Zero Dispersion Shifted Fiber
OSNR	Optical Signal to Noise Ratio
PMD	Polarization Mode Dispersion
PMD_Q	Statistical parameter for link PMD
PMF	Polarization Maintaining Fiber
SBS	Stimulated Brillouin Scattering
SMSPF	Singlemode Single Polarization Fiber
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
STM	Synchronous Transport Module
TBD	To Be Determined
WDM	Wavelength Division Multiplexing
WPNS	Water Peak not Specified
XPM	Cross-Phase Modulation

Part I

INTRODUCTION

1

INTRODUCTION

Optical fiber has come a long way since its first installed in the 1970s, when it was used mostly as long distance transmission over telephone signals. Since then, it has developed tremendously, people have now access to high speed internet in their home and offices through optical fiber cables. There exist a global network cable that links your computer and telephone to nearly all continents in the world. Today there exist several different types of optical fibers, each specialize in their own categories. There are fibers which provides ultra high speed data at short distances, fibers which can deliver data at very long distances, undersea optical fibers, fibers with special coating for harsh environment, fibers enhance for low attenuation, and other fibers for specific purposes.[17]

The origin of optical fibers lie in the invention of the laser in the 1960s. Scientist and engineers tried guiding laser light through optical fibers, but fiber in the 1960s had to much loss, in excess of 1000 dB/km. A breakthrough came in the early 1970 when they discovered that the losses could be reduced to 20 dB/km in the wavelength region near 1000 nm. At the same time GaAs semiconductor laser working at room temperature was achieved. The combination of a these inventions, a compact source and low-loss optical fibers led a worldwide effort for developing optical fiber communication systems.[22]

The real research in optical fiber communication systems started in 1975. Three decades later enormous progress has been made, optical fibers have revolutionized the telecommunications industry. Where it has become the backbone of the global telecommunications network, providing instant access to websites and telephones through out the world. The continuous reach of optical fiber network to homes and offices was in part thanks to companies such as internet service providers, cable television providers, telephone providers, and power providers that established their own fiber optic network.

The mass expansion of fiber optic network, was achieveable because the standardization organization such as the ITU-T. They made sure that various optical fiber manufacturer was developing optical fibers which was compatible with each other. This was an important step in the expansion of fibers through out the world, manufacturers making fibers had to be sure the connectors and splicers of the fibers was compatible with other ITU-T systems. Therefore, ITU-T have developed G.651 to G.657 Recommendations, detailing the characteristics of the fiber and their values.

There are other non-standard optical fibers existing in the market, not governed or developed by any standard organization. These non-standard fibers are often developed by the manufacturers themselves, or by some other business. These are usually for a niche market and produce in small volumes. These non-mainstream fibers have their properties altered to combat specific problems.

The optical fiber technology has clearly become an important part in the communication technology, and will continue to reach to more homes and offices everyday.

1.1 ORGANIZATION

The thesis is organized into four parts as follows:

THEORY
: Provides background information and fundamental theory on fiber optics

STANDARDS OF FIBER OPTIC SYSTEMS
: Provides information about standard fiber and a brief overview of the ITU-T Recommendation from G.651 to G.657, and also a brief comparison

NON-STANDARDS OF FIBER OPTIC SYSTEMS
: Provides information about non-standard fibers and a few selected example of non-standard fiber

CONCLUSION
: Provides a connclusion to the standard and non-standar fiber, and their influence in the optical fiber market

Part II

THEORY

2

THE BASIC OF FIBER OPTICS

2.1 HISTORY OF FIBER OPTICS

The ability to communicate by using light as a source has been around for many centuries, ancient cultures lights bonfires on top of hills to warn allies, but it wasn't until 1840s when Swiss physicist Daniel Colladon and French Jaques Babinet showed through an experiment that light can be guided along a jet of flowing water. When the stream of water poured to the bucket on the floor, a fixed light source can be directed to the opening and as amazement to the audience the light can be seen to bend along the stream of water. British physicist John Tyndall popularized this experiment in 1854 as shown in the figure 1 of how the experiment was made. These experiment coined the term for trapping light in solid is called total internal reflection and marked the first research in guided transmission of light.[16]

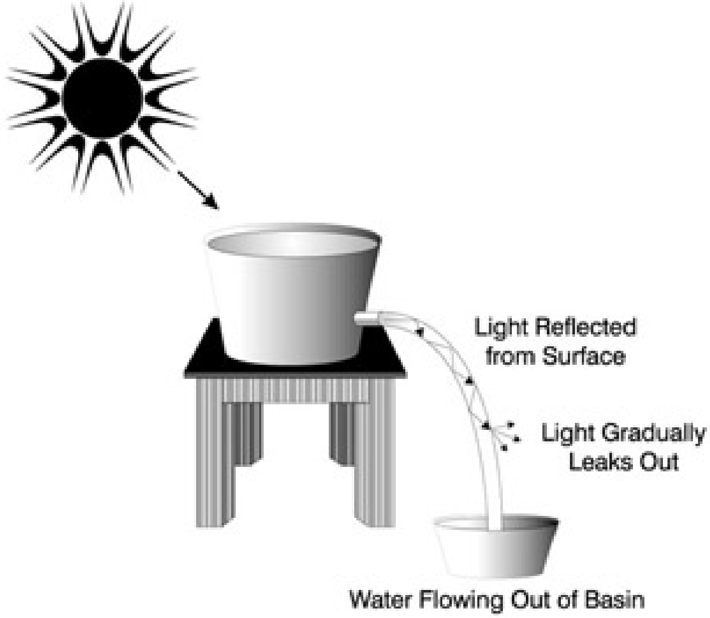

Figure 1: John Tyndall light bending experiment[16]

Inventors has since tried to adapt this new discovery for a more practical purpose, in the 1900s inventors tried to use glass rod to illuminate the inside of a pasients mouth. Another idea arise by bundling glass fibers together to transmit images from out of reach places, but several inventors was not succesful because light would easily leak through the surface. To solve the problem with light leakage, several scientist tried coating the glass rod in oils, beeswax and other materials with refractive index lower than glass. They did this because total internal reflection can occur when light travelling in one medium tries to enter another medium with lower refractive index. It wasn't before in 1956 when Larry Curtiss, an undergraduate student at University of Michigan, made the first glass-clad fiber by slipping a rod of glass with high refractive index into a tube of glass with lower refractive index. This paved way for new technologies in fiber bundling, which were the key to making endoscopes, gastroscopes and colonoscopes to examine inside a human body.[17]

Since the invention of the laser in 1960, inventors have tried to send information through fibers over long distances, but loss of light at long distances proved to be a problem at the time. Sending light through glass for 30 meters will retain only 0.1% of the light at the end, this loss is acceptable for medical usage such as endoscopes, but completely useless for communications. Many years is spent in tackling this problem, two engineers in 1966, Charles Kao and George Hockham found out that much of the loss of light was because of impurities in the glass and predicted that fiber made in high purified glass could retain 10% of the light at the end of a 500 meters long fiber. Years later in 1972 Robert Maurer, Donald Keck and Peter Schultz of Corning Glass Works, manage to create fibers in which 10% of the light remained after passing through 2.5 kilometers of fiber. Years of research and improvements of optical fibers has further enhance the distance of which lights can travel through fiber, and today's best optical fibers can boast an impressive distance of 50 kilometers where in which 10% of light is retained.[17]

2.2 WHAT IS LIGHT?

Since the 17th century scientist has been debating whether light is composed of waves or particles, Newton asserted that light is composed of tiny particles while Huygens stated that light was a wave. Neither of these theories at the time could be validated considering that the speed of light could not be measured accurately at the time. In the 19th century after the speed of light was measured by Léon Foucault which supported the wave theory, it seemed as though the particle theory has been proven wrong, but by the 20th century the particle theory gained traction among scientist. By studying the photoelectric effect scientist of the 20th century discovered that light both possessed the nature of electromagnetic waves and particles called photons. This phenomenon led to the characterization of light as a wave-particle duality.[17][26]

When viewing light as an electromagnetic wave, it is composed of an electric and magnetic wave which propagate together in space at the speed of light. As seen in the figure 2 the two waves are perpendicular to each other and to the direction it propagates. Whether a wave is transmitted from radio waves, heat from the oven, X-rays or from the sun, the electromagnetic radiation all shares the same fundamental wave-like properties. The amplitude of the wave varies sinusoidally, it starts from zero where it will rise to a positive peak before falling to a negave peak, then again returning to zero. This distance where light propagates to a complete cycle is called the wavelength and denoted by the symbol λ(lambda). The number of cycles per second is called the frequency and measured in hertz. The velocity for all electromagnetic waves travelling through vacuum is the speed of light(c) and is approximately $3.00\text{x}10^8 m/s$. The relationship between velocity, wavelength and frequency of electromagnetic waves is $c = \lambda f$.[17][45][29]

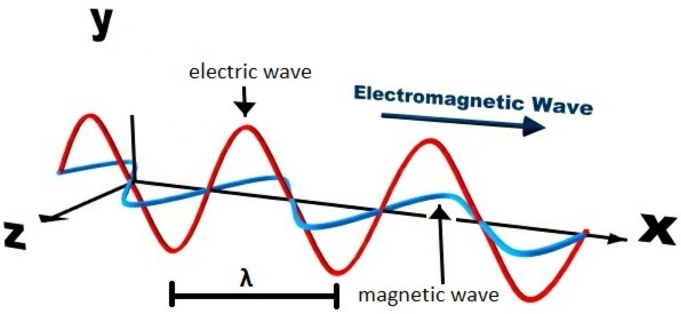

Figure 2: Propagation of an electromagnetic wave[38]

Light sources which emits pulses of light are groups of photons, which are a quantum of electromagnetic energy. The energy carried by a photon depends on how fast the wave oscillates, the faster a wave oscillates equals the higher the energy is being carried. A continuous wave is a series of photons emitted one after the other and each photon has its own energy set by the wavelength. The total energy of the wave correlates to the number of photons times the photon energy.[17]

White light is just a small part of the spectrum of electromagnetic radiation. As one can see from figure 3, the electromagnetic spectrum is the range for all possible frequencies of electromagnetic radiation. The spectrum goes from the highest energy of electromagnetic waves, which is the gamma rays and to the lowest energy levels, which is the radio waves. The higher the waves energy is, the deadlier it is for living organisms.[45]

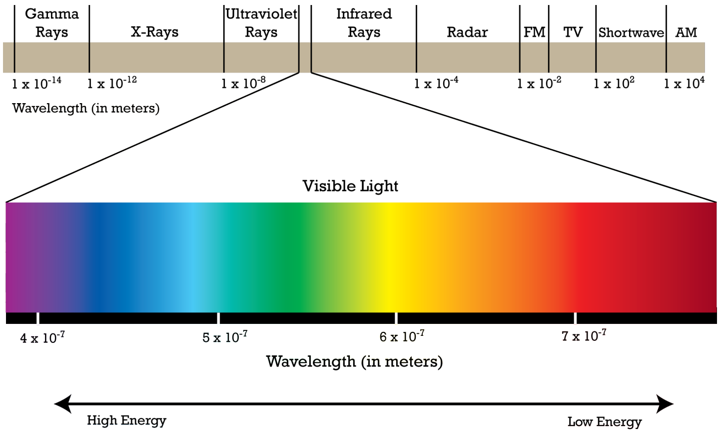

Figure 3: The electromagnetic spectrum[45]

The white light expanded in figure 3 shows the frequencies or energies of the electromagnetic spectrum to which our human eye responds to, when the engergies enter the eye, our brain can then interpret the signals as colours. The frequencies outside this spectrum is invisible to the eye, therefore humans cannot see for example x-rays.

2.3 REFRACTIVE INDEX

The speed of light in vacuum is regarded as the universal speed limit, only occasionally will it exceed this limit when light carries no information. Usually when light propagates through a medium its speed will be slower than its universal limit. The refractive index is a measured dimensionless unit which descripes the speed difference when the speed of light in vacuum enters another material, as equation 1 shows.[17]

$$n = \frac{c_{vacuum}}{c_{material}} \tag{1}$$

n	The refractive index
c_{vacuum}	The speed of light in vacuum
$c_{material}$	The speed of light in a material

From John Tyndall's water and light experiment in figure 1 in which one can observe that light is reflected to follow the stream of water. This phenomenon is called total internal reflection, it happens when light travels from one material with a higher refractive index to a material with lower index at a glancing angle. Long before this discovery physicist like Willebrord Snell discovered in 1621 that light bends to different angle depending on which medium it travels from and which medium it travels to, as illustrated in figure 4. The mathematical explanation of this phenomenon is named Snells law, shown in equation 2, it descripes the bending of light travelling from the surface depends on the refractive indexes of the two medium and the angle of indices at the surface. The angle of incidence and the angle of refraction of the transmitted light are measured from a line perpendicular to the surface called the normal.[17]

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{2}$$

n_1	Refractive index of initial medium
n_2	Refractive index of second medium
θ_1	Angles of incidence
θ_2	Angles of refraction

In fiber optics application one would want to trap light inside the fibers for as long as possible and retain as much light as possible. Utilizing what we know from Snell's law to gain total internal reflection in fibers, which would trap light along optic fibers. For example if glass has a refractive index 1.5 and air has a refractive index of 1.0, Snell's law becomes[17]:

$$1.5 \sin\theta_1 = 1.0 \sin\theta_2 \tag{3}$$

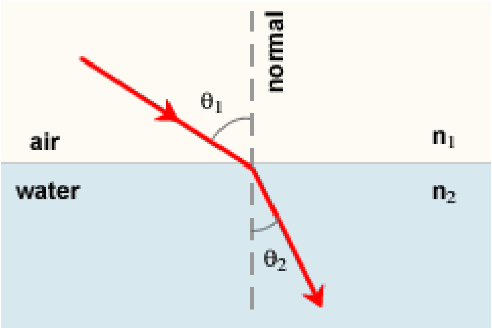

Figure 4: Light travelling from air and bends when travelling to water[40]

So instead of light bending in the direction closer to the normal, as in figure 4, the light would then bend farther away from normal, as figure 5. Which would accomplish the criteria for total internal reflection.

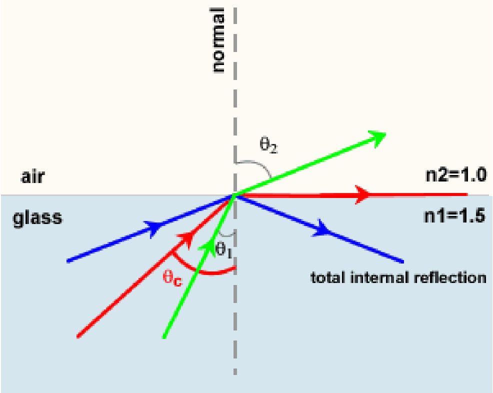

Figure 5: Illustration showing total internal reflection between to medium[40]

Snell's law indicates that refraction can't happen if the angle of incidence is too large, or if the angle exceeds a value called the critical angle, where the sine angle of refraction equal 1.0(which is the maximum value of the sine at 90°). The total internal reflection will instead bend the light back into the glass, it is this phenomenon which confines light inside optical fibers, as seen in figure 5. The critical angle which makes total internal reflection possible is derived by modifying Snell's law[17]:

$$\theta_{\text{crit}} = \arcsin \frac{n_2}{n_1} \tag{4}$$

In earlier example with refractive index for glass $n_1 = 1.5$ and for air $n_2 = 1.0$, the critical angle is then 41.8°. For any angle larger than the critical angle, will not be possible for Snell's law to solve, because the refracted angle would have a sine larger than 1.0, which is impossible.[17]

2.4 LIGHT GUIDING

In optical fibers, there are two important medium which enables light guiding, one is the core and the other is the cladding. The core being the inner part of the fiber, where light is guided. The cladding is the medium which encompasses the core and has a lower refractive index than the core, which properties allows for lights to reflect back to the core by total internal reflection, as illustrated in figure 6[17].

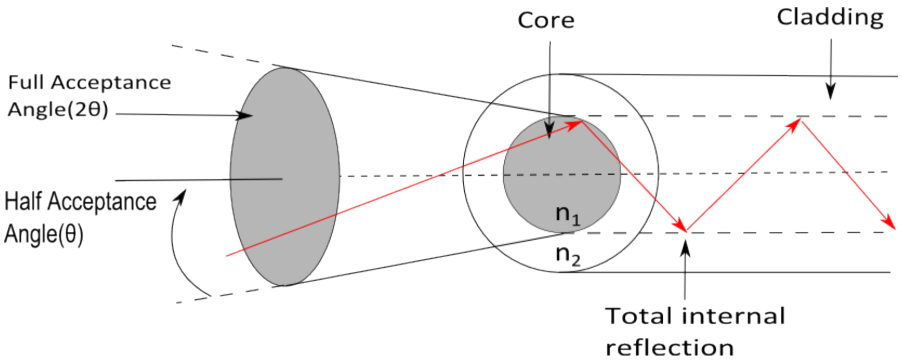

Figure 6: Light must fall within the acceptance angle in order to be guided inside the fiber

In order for light to first be able to enter the fiber, it must fall within an acceptable angle(θ), the angle that will allow light to be guided along its core, as shown in figure 6. The acceptance angle is measured in air from the outside of the core, therefore it differs from the confinement angle in the glass. This maximum acceptable angle of the fiber is measured as Numerical Aperture (NA), which equation 5 shows.[17]

$$\mathrm{NA} = \sin\theta = \sqrt{n_1^2 - n_2^2} \tag{5}$$

θ	Acceptance angle
n_1	Refractive index for the core
n_2	Refractive index for the cladding

2.5 TYPES OF OPTICAL FIBERS

Optical fiber is classified as either multimode or singlemode, and based on the way light propagate through it. There are two types of multimode fibers: step-index and graded-index. Understanding the characteristics of these fibers aides in understanding the applications for which they are used. Multimode fiber are designed for short distance communications and suited for LAN systems or video surveillance. Single mode fiber are designed for long distance communications and suited for telephony communications and multichannel television systems.[20][13]

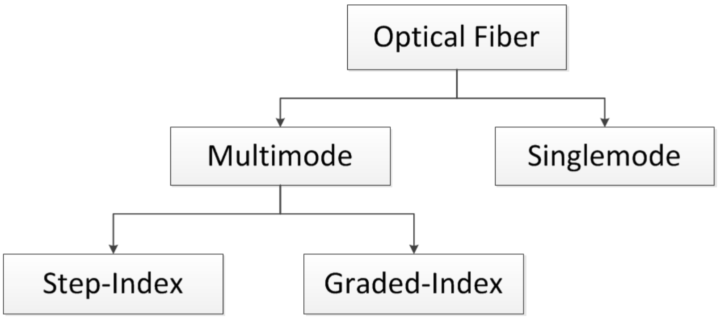

Figure 7: Types of glass fibers[20]

2.5.1 *Multimode Fiber*

Multimode fibers have a large core which allows for transmission of light using multiple propagation modes along the link, making it quite susceptible for modal dispersion. Because of its high dispersion, high attenuation and low bandwidth have limit its transmission of light to short distance communication. However, multimode fibers have many advantages: its ease of coupling to light sources and to other fibers, lower cost of light transmitters, and simplified connectorization and splicing processes.[20]

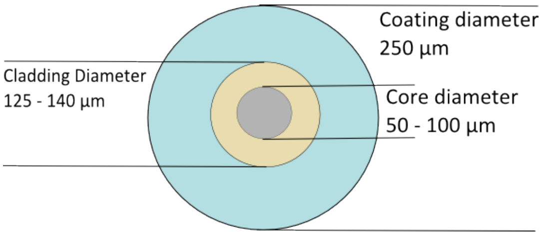

Figure 8: Typical diameters of multimode fibers[20]

2.5.1.1 *Step-Index Multimode Fiber*

Step-index multimode fibers are most used outside of the telecommunications field. Step-index fibers are relativ cheap to manufacture and were the first fibers developed for imaging. Step-index fibers guide light through the total reflection on the boundary between the core and the cladding, as seen in figure 9. As illustrates from figure 8, the fiber has a core diameter between 50 or 62.5 µm, a cladding between 100 and 140 µm, and a numerical aperture between 0.2 and 0.5.[28][20][17]

Because of modal dispersion, step-index multimode fiber have a very low bandwidth, and worsen as the distance increase, thereby limiting it to short distance communication. Plastic coating surrounds the fiber are mostly used to accommodate high attenuations for short distance communications.[20]

For communications purposes, step-index multimode fiber with a core at 100 µm and cladding at 20 µm, for a total diameter at 140 µm. Typically called the 100/140 fiber and uses a plastic coating to surround the fiber. The large core is attractive because it can collect light efficiently from cheap light sources, such as LEDs. The drawback from utilizing multimode fibers for communication is modal dispersion, which is an unavoidable result from carrying multiple modes. Modal dispersion however, is irrelevant for imaging and guiding illuminating beams, which is why this type of fibers is most used outside of communications.

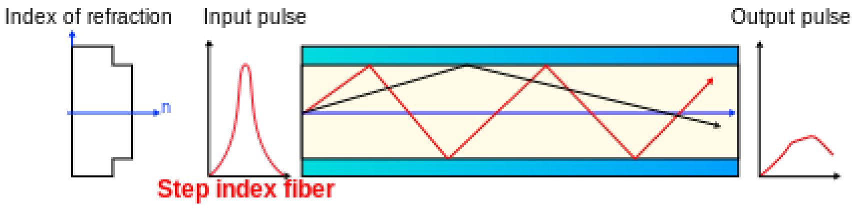

Figure 9: Light propagating through a step-index multimode fiber[25]

2.5.1.2 *Graded-Index Multimode Fiber*

Graded-index multimode fiber were developed for communication purposes as an alternativ to singlemode fiber, because engineers were in doubt if they could fit enough light into the core of singlemode fiber and unlike step-index multimode fiber where modal dispersion limited the capacity of these large core fibers. The core of the graded-index fiber possesses a non-uniform refractive index, decreasing gradually from the central axis to the inner edge of the cladding. This variation of refractive index forces the rays of light to propagate in a sinusoidal manner, as shown in figure 10. The higher the order of the mode, the longer a path it will have, but as the rays of light travels further from the axis, its speed will increase. In addition, graded-index fiber has smaller speed difference between the highest-order modes and the lowest-order modes, compared to step-index fiber. By developing this unique core for the graded-index fiber, has nearly eliminated modal dispersion for fibers with cores tens of micrometers in diameter, giving graded-index fiber much greater transmission capacity then step-index fiber.

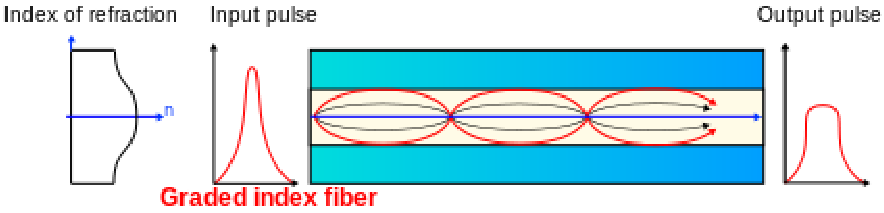

Figure 10: Light propagating through a grade-index multimode fiber[25]

2.5.2 *Singlemode*

Singlemode fiber, as the name implies, restrict transmission down the core to one ray of light at a time, as seen in figure 12 illustrates this. The advantage is higher performance with respect to bandwidth and attenuation. In order to restrict to only one mode, the core has to be small enough, as figure 11 shown, typical core diameter for singlemode is 8 to 12 µm. The reduced number of modes eliminates all forms of modal dispersion, modal noise and other effects following multimode transmission. Another advantage compared to multimode, is the ability to carry signals at a much higher speed. Singlemode is the standard choice for all kinds telecommunications that involve high data rates and communications over distances longer than a couple of kilometers.[20][17]

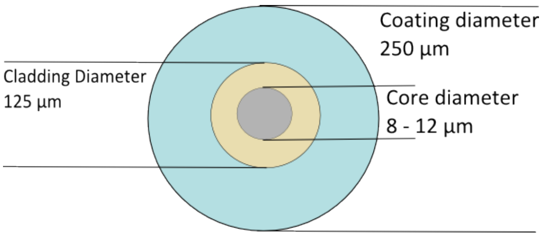

Figure 11: Typical diameter for singlemode fiber[20]

A singlemode fiber could achieve a speed up to 40 Gbps or above over long distances, if proper dispersion compensation components is used. One could further increase the system carrying capacity by injecting signals with varying wavelengths(wavelength division multiplexing) into one single fiber.[20]

The disadvantages of utilizing singlemode fibers, is because of the small core size, one would generally require more expensive light sources and alignment systems to achieve efficient coupling. Splicing and connectorization is also somewhat more complicated than multimode fibers. Nonetheless, these disadvantages are tolerable, because for high performance at long distances, singlemode are still preferable.[20]

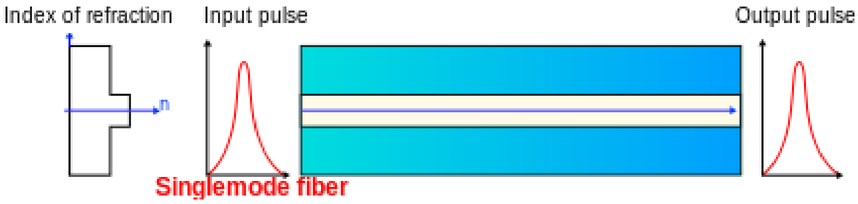

Figure 12: Light propagating through singlemode fiber[25]

2.6 REVIEW OF MULTIMODE AND SINGLEMODE FIBER

Table 1 provides a comparison between the two fiber types: singlemode and multimode fibers.

2.7 FIBER TRANSMISSION

Optical fiber system uses three basic components: a transmitter, a receiver and a transmission medium to pass light from one end to another. As with most material transmitting signals, degradation of signal can happen because of elements like poor

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

Table 1: Comparison between multimode and singlemode fiber[20]

transmitters or material, the same holds true for light passing through optical fibers. For optical fibers there are three principal effect which contributes to signal degradation, these are attenuation, dispersion and crosstalk. These effects contributes significantly to the performance of optical fibers.[17]

2.7.1 *Fiber Attenuation*

Attenuation is the reduction of signal strenght during transmission, if the signal attenuates too much, it becomes unintelligible.[43]

Attenuation in optical fibers is when the intensity of light fades through a medium. Usually the fault lies in light coupling into the fibers, absorption and dispersion within the fiber. Other times the fault could be with light leakage from fibers that suffer from severe microbending. Absorption and scattering are both effects which are cumulative and will increase with distance, while coupling losses will only occur at the end of fibers. Therefore the longer a fiber is, the more important are absortion and scattering losses, while coupling losses is less important and vice versa.[17]

The total attenuation is the sum of all losses, which is the sum of absorption, scattering and light-coupling losses. These losses are calculated given by equation 6[17].

$$P(D) = (P_0 - \Delta P)(1 - [\alpha + S])^D \tag{6}$$

D	Distance
P_0	Input Power
ΔP	Power lost
α	Light lost to absorption per unit length
S	Light lost to scattering per unit length
$P(D)$	Total power lost

Attenuation is measured in decibels, which are a logarithmic unit measuring the ratio between output and input power. The total attenuation loss is given by the equation 7. The negative sign is assure that negative negative numbers in attenuation measurements are avoided.[17]

$$dB = -10 \times \log_{10}(\frac{\text{output power}}{\text{input power}}) \tag{7}$$

2.7.1.1 *Light Absorption*

The absorption of light to the fiber material is happening when its energy is converted to heat due to molecular resonance and wavelength impurities. The amount of absorption depends on the materials electrons, all electrons vibrates at specific frequencies, known as their natural frequency. When light particles interact with an atom with the same natural frequency, this interaction causes the electrons in the atom to be excited and vibrate in a natural motion. This vibration will influence the neighboring atoms to vibrate in the same frequency, resulting in the energy transfer from vibration to heat. Figure 13 illustrates that light hitting a material will be either reflected, transmitted and absorbed.[44][20]

Different materials have different natural frequencies of vibration and thereby absorb different frequencies of light. By using this knowledge physicist are able to determine the properties and material composition of an object by observing which

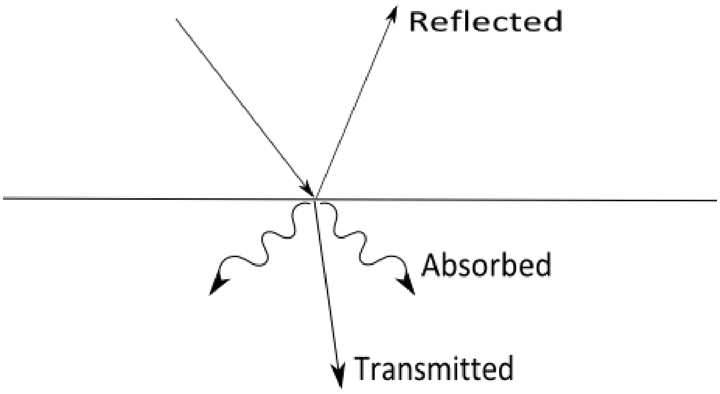

Figure 13: Illustration showing light reflected, transmitted and absorbed

frequencies of light it's able to absorb. Some materials can absorb light strongly and are opaque, while others are transparent. Glass is an important material for fiber optics, by adding impurities glass will be oqaque to certain wavelengths, or remove impurities to make it extremely transparent fiber, which is used for communications.[44][17]

Absorption is uniform, meaning that light propagating along a fiber will be absorb for the same fraction of light at the same wavelengths. It also has a cumulative properties, meaning when light passes through the fiber it will be absorb the same fraction of light for each unit length. By making fibers with the least absorbent properties, will allow light to propagate for long distances, which is a desirable trait.

2.7.1.2 *Rayleigh Scattering*

Another phenomenon which contributes to attenuation, is scattering, primarily Rayleigh scattering shown in figure 14. Light propagating in fibers will inevitably hit atoms and other materials, which will cause dispersion of the light in all directions, with some light escaping the core. The light energy that is returned down the core is known as backscattering.[17][20]

Similar to absorption, scattering has a cumulative and uniform characteristic. The farther light travels, the more likely scattering will occur.[17]

Scattering depends on the size of the particles relative to the wavelength of light. The closer a wavelength is to the particle size, the more scattering will occur. As the wavelength de-

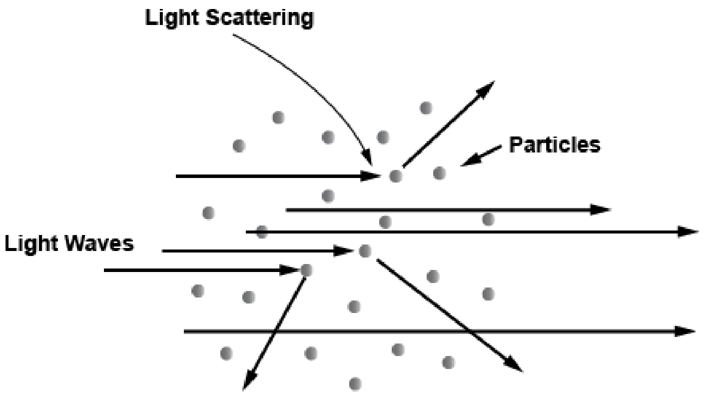

Figure 14: Rayleigh scattering of light[41]

creases, the amount of scattering will increase. Rayleigh scattering for example, is inversely proportional to the fourth power of the wavelength. When plotting the absorption spectrum of a fiber against the wavelength of the laser, certain fiber characteristics can be indentified. The plot in figure 15 illustrates the relationship between the wavelength of the injected light and the total fiber attenuation. The OH absorption peaks in the graph indicates at certain wavelength the presence of hydrogen and hydroxide ions in the fiber that causes an increase in attenuation. These ions are a result of water in the fiber from either manufacturing process or as humidity in the environment. The other absorption peaks are a product of metal impurities in the glass fibers. From the graph one can observe that attenuation with wavelength due to presence of water in single-mode fiber occurs mainly around 1383 nm. There is constantly an effort to improve the manufacturing process in order to minimize the amount of water peaks in fibers, for example fibers such as Cornings SMF-28e and OFS ALLWave from Lucent has overcame this problem. The absorption at wavelength farther than 1.6µm comes from silicon-oxygen bonds in the glass, as the graph shows, the absorption increases rapidly at longer wavelength. Knowing this, silica based fibers are rarely used for communication purposes at wavelength higher than 1.6µm.[17][20]

As one can see from the graph in figure 15, at shorter wavelength, Rayleigh scattering counts for most of the attenuation. As the wavelength decreases, Rayleigh scattering increases sharply. The space between the measured attenuation and the theoretical limits represents the absorption loss. The fraction of the total attenuation becomes larger as the two lines draws closer.

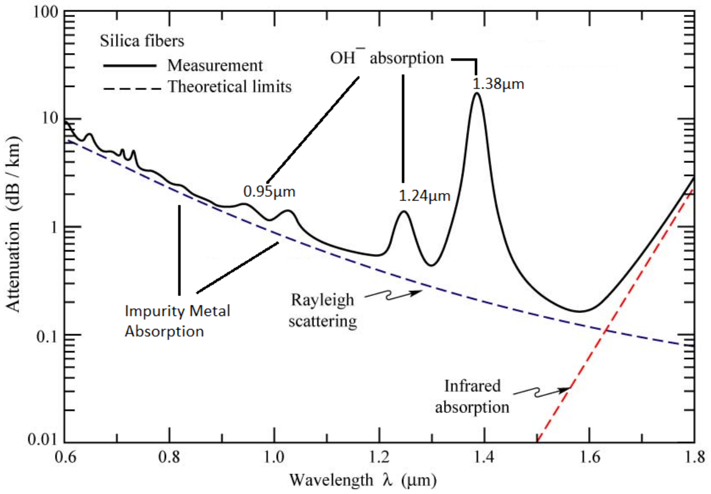

Figure 15: Measured attenuation in silica fibers and theoretical limits given by Rayleigh scattering in the short-wavelength region, and by molecular vibrations in the infrared spectral region[35]

Bands	Description	Range[nm]
	(1st window)	820 - 880
O Bands	Original(2nd window)	1260 - 1360
E Bands	Extended	1360 - 1460
S Bands	Short wavelength	1460 - 1530
C Bands	Conventional(3rd window)	1530 - 1565
L Bands	Long wavelength	1565 - 1625
U Bands	Ultra-long wavelength	1625 - 1675

Table 2: Different spectral bands[22]

In fiber optics communication it is the total attenuation that is important.[17]

For the main telecommunication transmission wavelengths, it is disireable to have wavelengths where the total attenuation is at a minimum. These wavelengths are known as the telecom windows. The table 2 shows additional windows, called bands, which is defined by the ITU-T G.692 standard and are dedicated to Dense Wavelength Division Multiplexing (DWDM) transmission systems.[20]

2.7.2 *Bandwidth*

A great advantage fibers have over copper wires, is low attenuation while maintaining high bandwidth to allow high speed communication over long distances. High bandwidth is what makes optical fibers so attractive, the ability to carry billions of bits per second over long distances. Bandwidth is crucial in communications, it is defined as the width of the frequency range that can be transmitted by an optical fiber. Bandwidth determined the maximum informaton that can be transmitted over a channel at a given distance. For multimode fibers bandwidth is only limited by modal dispersion, while for single-mode there are almost no limit to bandwidth.[20]

2.7.3 *Bending Loss*

Bending loss is when the fiber is bent at a sharp enough angle that light strikes the core-cladding interface at a large enough angle where lights can leak out, resulting in significant signal loss. Bending loss can be categorize in two category: macrobend and microbend. Macrobends are large bend in a fiber(with more than 2 mm radius), for example a fiber bent sharply where a cable ends at a connector. The macrobend performance, given as dB/turn, details the attenuation at a number of 360 degree turns around the given bend diameter of the fiber. Microbends are tiny kink or ripples that can form along a fiber that become squeeze into a small space. In other words, it's when the fiber core deviates from its own axis. Microbends are smaller than macrobends, but cause also light leakage because they affect the angle at which the light hits the core-cladding boundary. Microbends can be caused by multiple causes, such as manufacturing defects, mechanical constraints during fiber laying process and environmental variations(humidity, temperature, pressure) during its lifetime.[17][20][11]

2.7.4 *Dispersion*

Attenuation of copper wires increases with signal frequency, therefore copper wires cannot transmit information at high speeds. For optical fibers, attenuation does not depend on frequency, fibers have essentially the same attenuation across wide range of frequencies. Instead, the limitation on optical fiber bandwidth are mainly from dispersion. Dispersion is a phenomenon that reduces the effective bandwidth available for transmission. There exist three main types of dispersion in optical fibers: modal dispersion, chromatic dispersion and polarization mode dispersion, as shown in figure 16[17][20].

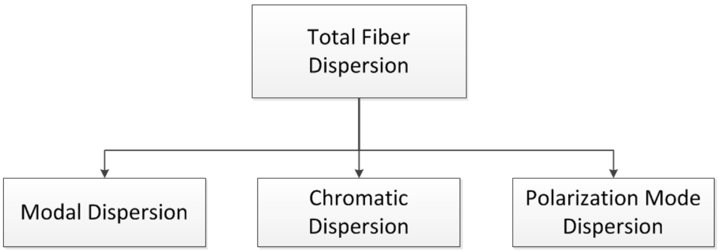

Figure 16: Types of dispersion

2.7.4.1 *Modal Dispersion*

Modal dispersion is the largest type of pulse dispersion in multimode step-index fibers. When injecting a very short light pulse into a fiber within the numerical aperture, all of the energy does not reach the end of the fiber simultaneously. The reason is because each mode has its own characteristic velocity, as if the injected light entered the fiber at a distinct angle. This causes pulses to spread out as they propagate along the fiber. The more modes the fiber transmit, the more pulses spread out. Figure 17 illustrates the phenomenon modal dispersion.[17][20]

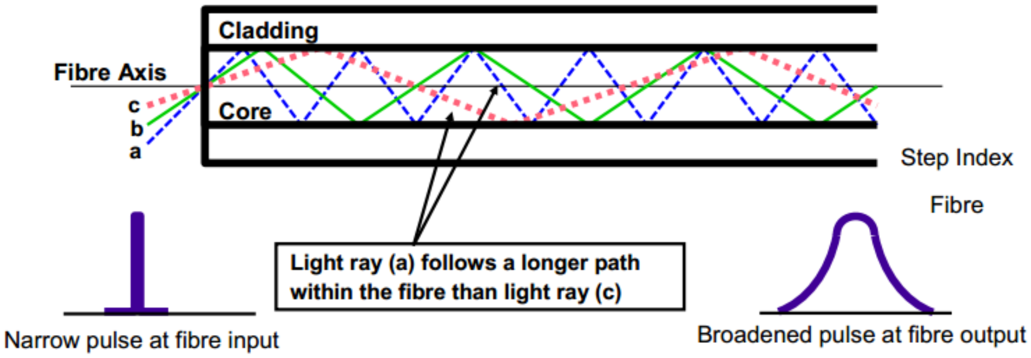

Figure 17: Modal dispersion in a fiber[15]

2.7.4.2 *Chromatic Dispersion*

Chromatic Dispersion (CD) occurs when glass fibers transmit a light pulse of different wavelengths, each travelling at different velocity. These different propagation of velocity broadens the light pulse as it arrives at the receiver, reducing the signal-to-noise ratio and increasing bit errors, as shown in figure 18[20].

Figure 18: Chromatic dispersion in a fiber[14]

CD is caused by two factors: material dispersion and waveguide dispersion. Material dispersion in glass fibers is caused by the variation of the refractive index in the material over wavelength. The higher the refractive index, the slower light travels. So a light pulse containing a number of wavelengths passing through a material, will stretch out, the wavelength with lower refractive index will be travelling faster than those with higher index. Waveguide dispersion arise from the distribution of light between core and cladding. Mainly a problem for singlemode fiber, in multimode penetration into the cladding is very small in a relative sense. In singlemode fiber, the wavelength of the light is not much bigger than the core and as a result the light travelling down the fiber travels in an area that exceeds the diameter of the core, which is called the mode field diameter of the fiber. The mode field diameter is a function of the wavelength of the light, with longer wavelengths equals a larger mode field diameter, as shown in figure 19. Parts of the light will travel in the geometric core of the fiber, while other part is travelling in the cladding. The light in the cladding will travel at a higher velocity than the core, since the refractive index in the core is higher than the cladding.[14][15][17]

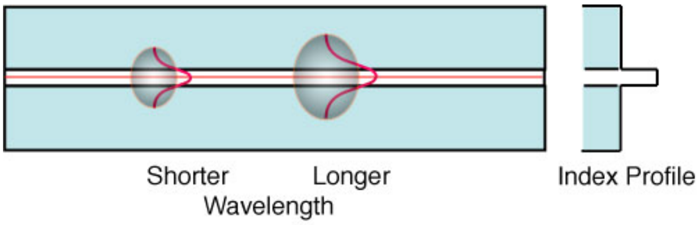

Figure 19: Waveguide dispersion[14]

2.7.4.3 *Polarization Mode Dispersion*

Polarization Mode Dispersion (PMD) is a property of single-mode fibers that affects the magnitude of the transmission rate. It's a phenomenon that results from the difference in propagation velocity of the energy of a given wavelength, which is split into two polarization axes perpendicular to each other and causing dispersion, as shown in the figure 20[20].

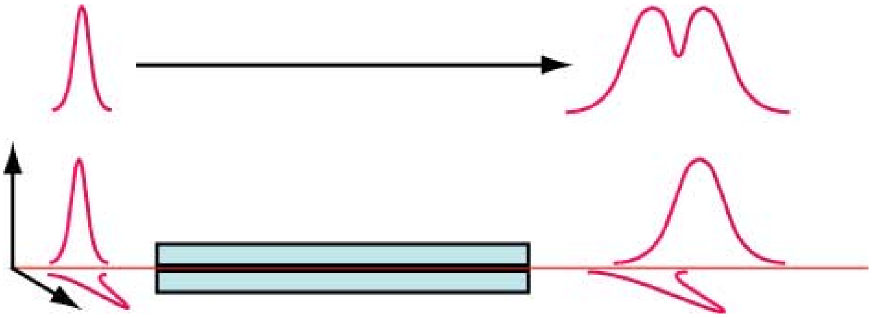

Figure 20: Polarization mode dispersion[14]

PMD is caused by the birefringence or called double refraction, which can influence two factors: material birefringence and waveguide birefringence. Waveguide birefringence is caused by the geometrical shape of the fiber such as concentricity, oval core or oval fiber, shown in figure 21. Material birefringence is caused by external stress induced on the fiber such as macro bending, micro bending, twisting or temperature variations, shown in figure 22[20][14].

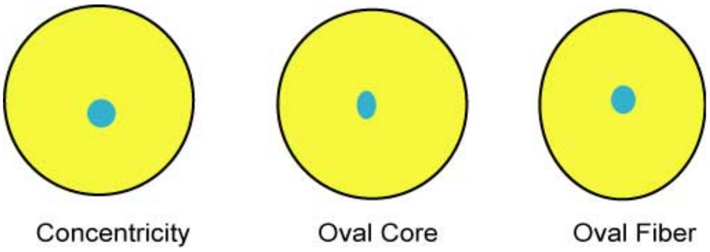

Figure 21: Waveguide birefringence examples[14]

The PMD is also the mean value of all Differential Group Delays (DGD) and is expressed in picoseconds. The PMD(mean DGD) can cause transmission pulse to broaden when it's transmitting along the fiber. This causes distortion, increasing the

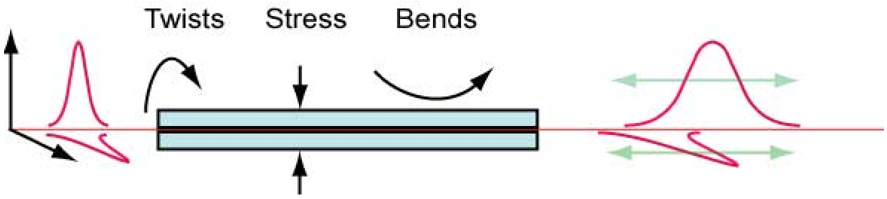

Figure 22: Material birefringence examples[14]

bit error rate of the optical system. The main issue with PMD is that it limits the transmission bit rate on a link. Therefore, it's important to know the PMD value of the fiber in order to calculate the bit rate limits of the optical fiber link.[20]

2.7.5 *Nonlinear Effects*

Nonlinear effects are processes which effect optical signals from the interactions between light waves and the material transmitting them. It's called Nonlinear effect because their strength depends on the square(or some higher power) of intensity rather then simply on the amount of light present, which means that nonlinear effects are weak at low powers, but can become stronger once light reaches high intensity. Ligh can reach a higher intensity when either power is increased or when light is concentrated in a small area, such as the core of the optical fiber.[17]

Nonlinear effects are potentially important in optical fibers, while some can become problematic factors in transmission systems. Some occurs in system carrying only one channel, while others can occur in multichannel systems such as DWDM system. Nonlinear effects can be divided in two categories:[17][20]

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

2.7.5.1 *Self-Phase Modulation*

When light travels through glass fibers its speed can change, because the refractive index of the glass varies slightly with the intensity of the light, so this variation of signal intensity cause changes to the speed of light. This process cause intensity modulation of an optical channel to modulate the phase of the optical channel that creates it, this effect is what's SPM. As the intensities of the signal increase, the light induces local variable changes in the refractive index of the fiber, this effect is called the Kerr effect, this causes a time-varying phase in the same channel. Which modulates the phase of the transmitted wavelengths, causing the wavelengths spectrum of the transmitted signal to broaden. This spectral broadening produces dispersion-like effect, which can limit data rate in some long overhaul communications systems. In some advanced network systems, the SPM can be used to slightly compensate for the effects of chromatic dispersion, because wavelengths shift of SPM causes the exact opposite of positive chromatic dispersion.[17][20]

2.7.5.2 *Cross-Phase Modulation*

Similar to SPM, XPM is caused by the Kerr effect, but XPM are only present during multichannel transmission. XPM is the effect when a signal in one channel has on the phase of another. The strength of XPM increases with the number of channels, and becomes stronger as the channel spacing becomes smaller. Methods to mitigate this effect can cause a limit to transmission speed.[17][20]

2.7.5.3 *Four-Wave Mixing*

FWM is an interference phenomenon which can occur in multichannel transmission where two or more signal frequenciescan combine and produce unwanted signals, for example when three signals($\lambda_4 = \lambda_1 + \lambda_2 - \lambda_3$) combine and produce a fourth unwanted channel, also known as a ghost channel.[20]

FWM is the strongest nonlinear effect in DWDM systems, where optical channels are typically close and spaced on a frequency grid tycially seperated by 100 or 200 GHz. In DWDM systems with many channels, FWM can cause alot of ghost channels which overlaps with actual signal channels, due to the high power levels. For example in 4-channel system it could produce 24 ghost channels and with a 16-channel system will produce

1920 ghost channels. Therefore FWM is one of the most adverse nonlinear effect for DWDM systems.[17][20]

FWM is a weak effect, but it can accumulate when different wavelengths travelling at the same speed and remain at a constant phase over long distances, which happens with systems using dispersion-shifted fiber where chromatic dispersion is very close to zero. This problem led to an abandonment of zero dispersion-shifted fiber, the zero-dispersion point was then moved out of the DWDM band to overcome this problem. In standard fiber, non-dispersion-shifted fiber, even with modest amount of chromatic dispersion around the zero dispersion wavelength(1550 nm), the signals at different wavelengths quickly drift out of phase, reducing FWM effect. A reduction in FWM effects can also be achieved by using irregular channel spacing.[17][20]

2.7.5.4 *Stimulated Raman Scattering*

When a fiber transmit two suitable spaced wavelengths, SRS can transfer energy from the signal with shorter wavelengths to the signal with longer wavelengths. This effect occurs when light waves interact with molecular vibrations in a solid lattice. The molecule absorbs the light, then re-emits a photon with an energy equal to the original photon with the additional energy of the molecular vibration mode. This effect will both scatter light and shift its wavelength. During the transfer of energy, there can be crosstalk between optical channels. In addition it can also deplete signal strength of one light energy, and amplify another wavelengths outside the operating band. In order to minimize the SRS effect, careful choice of wavelengths can considerably reduce interference between SRS and other channels. With multichannel systems such as DWDM, SRS can impose strict limit to the system, where its effect are more serious with shorter wavelengths.[17][20]

2.7.5.5 *Stimulated Brillouin Scattering*

SBS is a backscattering phenomenon which scatters light back towards the transmitter, thereby causing loss of power, and unlike SRS it can occur when only a single channel is transmitted. SBS can occur when signal power reaches a level sufficient enough to generate tiny acoustic vibrations in the glass. Acoustic waves can change the density of the glass, thereby altering the refractive index, this process can scatter light which is known as Brillouin scattering. The light being scattered can generate its own acoustic wave, this process is known as stimulated Brillouin scattering. SBS effects occurs during transmission of only a few channels.[17][20]

2.8 CLASSIFICATIONS OF OPTICAL FIBERS

Optical fibers can be grouped in several categories, based on their characteristics, structure and material. For example silica optical fibers can be grouped into two categories: solid core/cladding fiber and air silica holey fiber. Each category can then be further divided into either singlemode or multimode fiber. Again, depending on their purposes, they can be grouped into each category. Table 3 shows the classification of optical fibers.

Solid Core/Cladding Fiber	Multimode Fiber	Modal delay optimized MMF	Graded index 50μm core MMF
	Singlemode Fiber	Dispersion tailored SMF	DSF, DCF, DFF, NZ-DSF
		Birefringence controlled SMF	PMF, SMSPF
		Nonlinear SMF	Raman Fibe, Brillouin Fiber
		Photonic device SMF	Rare earth doped SMF, Photosensitive Fiber, Attenuation Fiber
Air Silica Holey Fiber	Multimode Fiber	Large N.A. MMF	Large N.A. large core fiber for lase delivery
	Singlemode Fiber	Dispersion tailored SMF	DSF, DCF, DFF, NZ-DSF
		Birefringence controlled SMF	PMF, SMSPF
		Nonlinear SMF	Raman Fibe, Brillouin Fiber
		Photonic device SMF	Rare earth doped SMF, Photosensitive Fiber

Table 3: Classification of optical fiber[27]

Part III

STANDARDS OF FIBER OPTIC SYSTEMS

3

STANDARDS OF FIBER OPTIC SYSTEMS

With rapid deployment of optical fiber communication system worldwide, agreements on key characteristics and measurement are required to draw a consensus on common standard system for optical fibers. Today standards are being characterize and developed by organizations such as International Electrotechnical Commission (IEC), International Standards Organization (ISO) and ITU Telecommunication Standardization Sector (ITU-T) to name a few, the main focus of this study is primarily about ITU-T standards. Their work has helped with defining the technologi and architecture of the fiber optical transport system. Development of the standard gives a technical specification giving shape to the global telecommunications infrastructure[37].The main organization on standardization for fiber optic telecommunication technique is ITU-T, where standardizations are published as "Recommendations" by thirteen study groups within ITU-T. These study groups are comprised of specialist from industry, the public sector and R&D entities worldwide who meets regularly to eliminate any unnecessary spesification to ensure that each piece of communication system can interoperate seamlessly with the elements that make up today's complex Informations and Communication Technologies (ICT) networks and services. The result of this cooperative effort leads industry players to drop their competitive rivalries aside in favour of building a global consensus on new technologies. The ITU-T Recommendations are the bedrock underpinning the modern ICT networks that serve as the lifeblood of virtually every economic activity, from manufacturer to purchaser.[27][18]

Among the Recommendations, the following series are closely related to optical fibers and cables: series G(Transmission systems and media, digital systems and networks), series K(Protection against interference) and series L(Construction, installation and protection of cables and other elements of outside plant). But for characteristics of optical fiber systems, the series G.651 - G.657 are the relevant part. Table 4 provides and overview of the optical fibers specified by ITU-T[27].

ITU-T Recommendation	Fiber Category
G.651.1	50/125 µm multimode gradient index optical fiber
G.652	Single mode optical fiber
G.653	Dispersion shifted single mode optical fiber
G.654	Cut-off shifted single mode optical fiber
G.655	Non-zero dispersion shifted single mode optical fiber
G.656	Non-zero dispersion shifted single mode optical fiber for wideband optical transport
G.657	Characteristics of a bending-loss insensitive single-mode optical fibre and cable for the access network
See appendix for all Recommendations attributes from table 30 to 36	

Table 4: Overview of the optical fiber standards specified by ITU-T[27]

3.1 INTERNATIONAL STANDARDS FOR MULTIMODE FIBERS

The standard G.651 was withdrawn in 2008 when its content became obsoleted following the new standard, G.651.1 on multimode fiber applications in optical access networks.

3.1.1 *G.651.1 Characteristics of a 50/125 µm multimode graded index optical fibre cable for the optical access network*

The main scope for this Recommendation, is the network in a multi-tenant building. A substantial amount of all customers in the world are living in these buildings, and multimode fiber has also becoming more popular in the horizontal cabling in the Fiber to the Zone (FTTZ) architecture. Due to the high connections density and short distribution lengths, making use of the 50/125 µm graded-index multimode fiber, this high capacity optical network can be designed and installed cost-effectively. The use of this network has been shown to use for datacom in enterprise buildings with system bit rates ranging from 10 Mbit/s to 10 Gbit/s.[2][9]

This Recommendation describes a 50/125 µm graded-index multimode optical fiber which is suitable for use in the 850 or 1300 nm region, or alternatively may be used in both wavelength simultaneously.[2]

The G.651.1 Recommendation, recommends the use of quartz multimode fiber for access network in specific environments. These environments are multi-tenant building sub-networks in which broadband services have to be individually delivered to each apartments. Therefore, the recommended multimode fiber supports the cost-effective use of 1 Gbit/s Ethernet system over link length up to 550 m, and usually based upon the use of 850 nm light source(transmitter).[2]

Table 5 list a couple of attributes for the Recommendation. Following the release of this Recommendation, a new bend standard with a tighter bend radius requirement. This new standard specify a bend performance at a radius of 15 mm, currently there are no multimode fiber that defines a tighter bend radius performance[19], which makes this fiber a bend-insensitive multimode fiber. The benefits from using a bend-insensitive fiber is minimizes bend-induced attenuation, thereby freeing spare operating margin, which helps maximize system reliability, minimize downtime and provides opportunities for cost reduction. In addition, bend-insensitive fiber allows for installation in more places than regular fibers, because of the abiltity to withstand tigh bends and challenging cabling routes without substantially less signal loss.[9]

Despite the significant cost savings, some end users are still preferring singlemode fibers for campus and other enterprise network links. The majority of enterprise network links including campus backbones, are less than 100 m and more than 95% are less than 250 m in length. Both of these distances are achievable by multimode fibers with high speed capacity. Therefore it's an advantage to switch to these bend-insensitive multimode fibers for these short distances, to get the performances you need at a significant lower cost.[9]

G.651.1		
Attribute	Description	Value
Cladding diameter	nominal and tolerance	125 ±2 µm
Core diameter	nominal and tolerance	50 ±3 µm
Macrobend loss	Radius	15 mm
	Number of turns	2
	Max at 850 nm	1 dB
	Max at 1300 nm	1 dB
Attenuation	Max at 850 nm	3.5 dB/km
	Max at 1300 nm	1.0 dB/km
See appendix for the rest of the attributes		

Table 5: G.651.1 fibre attributes[2]

3.2 INTERNATIONAL STANDARDS FOR SINGLEMODE FIBERS

3.2.1 *G.652 Characteristics of a singlemode optical fiber and cable*

The first singlemode fiber specified by the ITU-T was the Recommendation G.652, and often called the standard singlemode fiber. This fiber was the first to be deployd in public network and represents a large majority of the fibers that were installed. The Recommendation G.652 is the foundation to modern optical networks that are the basis for all modern telecommunication.[22]

This Recommendation for ITU-T G.652 descripes the various attributes for a singlemode optical fiber which has a zero-dispersion wavelength around 1310 nm, but can also be used around 1550 nm region. This Recommendation was originally release in 1984, but have been improved in many versions thereafter, this new revision is intended to continue the commercial success of this fiber worldwide.[3]

Over the years, following the release of new revisions, new attributes and parameters were added or changed to the Recommendation G.652. These changes spawn new categories within the Recommendation. The consensus was that some applications would need these new attributes and parameters, but there were still some applications that wouldn't need them. Therefore some options were needed, it was agreed to create different categories of ITU-T G.652 fibers. The new categories were given name: G.652.A, G.652.B, G.652.C and G.652.D, which were distinguished by their attenuation requirements, Statistical parameter for link PMD ($\mathrm{PMD_Q}$) specification, whether the fiber is Low Water Peak (LWP) or Water Peak not Specified (WPNS) and their intended applications.[3]

The G.652 fibers have certain common values, such as the maximum magnitude of chromatic dispersion at $D_{1550} = 17$ $ps/(nm \times km)$, which is one of the highest among the singlemode fibers.[3]

3.2.1.1 *G.652.A*

The Recommendation G.652.A is a 20th century standard that does not support today's technology, and is characterize by its $\mathrm{PMD_Q}$ value of 0.5 $ps/\sqrt{km}$, as seen from table 6. Its performance is specified for use at 1310 nm and 1550 nm, where the chromatic dispersion is zero near 1310 nm, while a loss at the minimum near 1550 nm. ITU-T G.652.A support the use of applications such as those recommended in ITU-T G.957 and G.691 up to Synchronous Transport Module (STM)-16, as well as 10 Gbit/s up to 40 km(Ethernet) and STM-256 for ITU-T G.693.[27][10][3]

G.652.A		
Attribute	Description	Value
Attenuation coefficient	Max at 1310 nm	0.5 dB/km
	Max at 1550 nm	0.4 dB/km
PMD coefficient	Max $\mathrm{PMD_Q}$	0.5 $ps/\sqrt{km}$
See appendix for the rest of the attributes		

Table 6: G.652.A fiber attributes[3]

3.2.1.2 *G.652.B*

The ITU-T G.652.B is an upgrade from the G.652.A in terms of PMD and attenuation. G.652.B has a lower $\mathrm{PMD_Q}$ of 0.20 $ps/\sqrt{km}$ than G.652.A with its 0.5 $ps/\sqrt{km}$, and the attenuation coefficient is also reduced to 0.4 and 0.35 dB/km for 1310 nm and 1550 nm, seen in table 7. Also, G.652.B defines the attenuation coefficient at 1625 nm to be at an equal level as in 1310 nm in order to faciliate the usage of L-band, from 1565 to 1625 nm. These enhancements in PMD and attenuation attributes makes the G.652.B more suiteable than G.652.A for higher data rate and longer link distance communication. G.652.B support higher bit-rate applications up to STM-64, such as some in ITU-T G.691 and G.692, and STM-256 for applications in ITU-T G.693 and G.959.1. Chromatic dispersion accommendation may be necessary depending on the applications in use.[27][3]

G.652.B		
Attribute	Description	Value
Attenuation coefficient	Max at 1310 nm	0.4 dB/km
	Max at 1550 nm	0.35 dB/km
	Max at 1625 nm	0.4 dB/km
PMD coefficient	Max PMD_Q	0.20 $\text{ps}/\sqrt{\text{km}}$
See appendix for the rest of the attributes		

Table 7: G.652.B fiber attributes[3]

3.2.1.3 *G.652.C*

The more recent ITU-T G.652.C are not specified for 1625 nm, but includes an additional communication window in E-band, by significantly reducing OH absorption peak near 1383 nm, commonly referred as the water peak. Except for the additional communication window band, its attribute is quite similar to ITU-T G.652.A, its PMD_Q value is the same as for the G.652.A. Furthermore, the attenuation coefficient specification at 1383 ± 3 nm has been added to specify the attenuation level in the E-band, Whose value is equivalent to those of O-band at 1310 nm and L-band at 1625 nm, shows in table 8. The G.652.C also provides the wides bandwidth of optical communication windows: O, E, S, C and L bands in the fiber. By lowering the attenuation and opening the full spectrum for transmission, the number of channels you can transmit increases by 33% through Coarse Wavelength Division Multiplexing (CWDM).[27][10]

3.2.1.4 *G.652.D*

The most recent of the categories, ITU-T G.652.D, its attribute is similar to the G.652.B, but allows its transmission in portions

G.652.C		
Attribute	Description	Value
Attenuation coefficient	Max at 1310 nm to 1625 nm	0.4 dB/km
	Max at 1383 nm ± 3 nm	0.4 dB/km
	Max at 1550 nm	0.3 dB/km
PMD coefficient	Max PMD_Q	0.5 $\text{ps}/\sqrt{\text{km}}$
See appendix for the rest of the attributes		

Table 8: G.652.C fiber attributes[3]

of an extended wavelength range from 1360 to 1530 nm. This fiber is the most up to date with today's technology, according to fiber optic expert at Corning[10], the ITU-T G.652.D provides not only the maximum return of your investments, but also affords it the best protection and recommended as the fiber of choice when deploying singlemode optical fiber.[3][10]

ITU-T G.652.D is an upgrade from the ITU-T G.652.C, being that its also a low water peak optical fiber and function in the same wide bandwidth of optical communication window, but its PMD_Q is reduced to 0.20 $\text{ps}/\sqrt{\text{km}}$ compared with 0.5 $\text{ps}/\sqrt{\text{km}}$ in G.652.C, shows in table 9. This reduction in PMD_Q enables G.652.D to enhance the high bit-rate capacity as in the case for G.652.B. Just like the G.652.C, The G.652.D attributes and large effective area, which lower the incidence of nonlinear effects, enables it to support CWDM systems.[27][20]

3.2.1.5 *Review of the Recommendation G.652*

Table 10 summarize the categories of the ITU-T G.652.

3.2.2 *G.653 Characteristics of a dispersion-shifted, single-mode optical fibre and cable*

This Recommendation describes a dispersion-shifted optical fiber which has a nominal zero-dispersion wavelength which is shifted from 1310 nm to the spectral region close to 1550 nm, where

G.652.D		
Attribute	Description	Value
Attenuation coefficient	Max at 1310 nm to 1625 nm	0.4 dB/km
	Max at 1383 nm ± 3 nm	0.4 dB/km
	Max at 1550 nm	0.3 dB/km
PMD coefficient	Max PMD_Q	$0.20\ \text{ps}/\sqrt{\text{km}}$
See appendix for the rest of the attributes		

Table 9: G.652.D fiber attributes[3]

the optical loss is minimum and Erbium Doped Fiber Amplifier (EDFA) gain is available, and a dispersion coefficient which is monotonically increasing with wavelength. There exist two fiber categories for the Recommendation G.653: G.653.A and G.653.B, both functioning in the wavelength 1550 nm region, but could function around 1310 nm at constraints where the attenuation coefficient perform below 0.55 dB/km. Some provisions are made to enable the fiber to transmit at longer wavelength up to 1625 nm and lower down to 1460 nm. At these wavelengths, the chromatic dispersion coefficients may be specified to support CWDM systems that do not have significant impairment due to non-linear effects. Otherwise, the G.653 optical fiber is only suited to high bit-rate applications at 1550 nm over longer distances.[6][27]

The fiber categories of ITU-T G.653 is distinguished based on PMD requirements and chromatic dispersion specifications.

3.2.2.1 *G.653.A*

ITU-T G.653.A is an early version of Dispersion-Shifted Fiber (DSF), it have a zero dispersion wavelength, λ_0, in the range of 1500 to 1600 nm along the positive dispersion slope of λ_0 given by $S_0 \leqslant 0.085 ps/nm^2 \times km$, table 11 shows. The LP_{11}(second-order) mode cut-off is set to 1270 nm, which is longer than G.652 fiber by 10 nm. The macrobend loss limit is increased to 0.5 dB for 30 m bending radius and for 100 turns, compared to 0.1 dB for G.652. The maximum attenuation coefficient of 0.5 dB/km at 1550 nm is also higher than G.652 with 0.3-0.4 dB/km. The chromatic dispersion wavelength range of the

G.652			
	Characteristics	Wavelength Coverage	Applications
G.652.A	Max PMD$_{Q}$=0.5 ps/$\sqrt{\mathrm{km}}$	O and C bands	Support applications such as those recommended in ITU-T G.957 and G.691 up to STM-16, as well as 10 Gbit/s up to 40 km(Ethernet) and STM-256 for ITU-T G.693
G.652.B	Maximum attenuation specified at 1625 nm. Max PMD$_{Q}$=0.2 ps/$\sqrt{\mathrm{km}}$	O, C and L bands	Support higher bit-rate applications up to STM-64, such as some in ITU-T G.691 and G.692, and STM-256 for applications in ITU-T G.693 and G.959.1.
G.652.C	Maximum attenuation specified at 1383 nm(equal or lower than 1310 nm). Max PMD$_{Q}$=0.5 ps/$\sqrt{\mathrm{km}}$	O, E, S, C and L bands	Similar to G.652.A, but this standard allows transmission in portions of an extended wavelength range from 1360 nm to 1530 nm. Suiteable for CWDM systems.
G.652.D	Maximum attenuation specified from 1310 to 1625 nm. Maximum attenuation specified at 1383 nm(equal or lower than 1310 nm). Max PMD$_{Q}$=0.2 ps/$\sqrt{\mathrm{km}}$	O, E, S, C and L bands	Similar to G.652.B, but this standard allows transmission in portions of an extended wavelength range from 1360 nm to 1530 nm. Suiteable for CWDM systems.

Table 10: G.652: Charateristics of singlemode optical fiber and cable[20]

ITU-T G.653 is over S+C+L band. In spectral range between 1525 nm $< \lambda <$ 1575 nm, the maximum magnitude of chromatic dispersion is $D_{max} = 3.5 ps/nm \times km$, with the zero dispersion wavelength lies between 1500 to 1600 nm.[6][27]

As specified ITU-T, the G.653.A is suitable for the systems in ITU-T G.691, G.692, G.693, G.957 and G.977 with an unequal channel spacing in the 1550 nm wavelength region.[6]

Many supmarine applications can utilize this category. For some submarine applications, the full optimization can lead to choosing different limits than are specified by the standard. An example could be to allow cable cut-off wavelength values to be as high as 1500 nm.[6]

3.2.2.2 *G.653.B*

ITU-T G.653.B attributes are similar to the G.653.A, but the more stringent PMD requirements allows STM-64 systems to lengths longer than 400 km and ITU-T G.959.1 Non-Return-to-Zero (NRZ)

G.653.A		
Attribute	Description	Value
CD coefficient	λ_{min}	1525 nm
	λ_{max}	1575 nm
	D_{max}	3.5 ps/(nm × km)
	λ_{0min}	1500 nm
	λ_{0max}	1600 nm
	S_{0max}	0.085 ps/(nm^2km)
Attenuation coefficient	Max at 1550 nm	0.35 dB/km
PMD coefficient	Max PMD_Q	0.5 ps/$\sqrt{km}$
See appendix for the rest of the attributes		

Table 11: G.653.A fiber attributes[6]

40G applications. This category may also support CWDM applications which do not have significant non-linear impairments. It has also a reduced 0.20 ps/$\sqrt{km}$, table 12 shows, compared to 0.5 ps/$\sqrt{km}$ of the G.653.A, the low PMD_Q requirements added to G.653B enhance the high bit-rate capacity.[22][27]

G.653.B		
Attribute	Description	Value
CD coefficient	$D_{min}(\lambda)$:1460-1525 nm	0.085(λ-1525)-3.5
(ps/nm×km)	$D_{min}(\lambda)$:1525-1625 nm	3.5/75(λ-1600)
	$D_{max}(\lambda)$:1460-1575 nm	3.5/75(λ-1600)
	$D_{max}(\lambda)$:1575-1625 nm	0.085(λ-1575)+3.5
Attenuation coefficient	Max at 1550 nm	0.35 dB/km
PMD coefficient	Max PMD_Q	0.5 ps/$\sqrt{km}$
See appendix for the rest of the attributes		

Table 12: G.653.B fiber attributes[6]

3.2.2.3 *Review of the Recommendation G.653*

Table 13 summarize the categories of the ITU-T G.653.

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

Table 13: G.653: Characteristics of a dispersion-shifted single-mode optical fibre and cable[20]

3.2.3 *G.654 Characteristics of a cut-off shifted singlemode optical fibre and cable*

This ITU-T Recommendation G.654, defines a characteristics of the cut-off shifted singlemode optical fiber and cable which has a zero-dispersion wavelength around 1300 nm, which is loss-minimized and cut-off shifted at wavelength around 1550 nm and optimized for use in the region 1530 to 1625 nm.[22][8]

The main features of this Recommendation, are its longer cut-off wavelength and lower attenuation coefficient at 1550 nm compared to other singlemode optical fibers. The longer cut-off wavelength allows for a lower macrobend loss design, which can be advantageous to submarine cables, which requires lower attenuation. The lower attenuation coefficient arise from certain processes and not from its characteristics, processes such as frabrication process, fiber composition, fiber design and cable design. Attenuation coefficent values at 0.15 to 0.19 dB/km in the 1550 nm vavelength are desireable trait, which has been achived for this Recommendation. Where these features are suiteable for long-haul transmission in the 1530 to 1625 nm region.[22]

There exist four categories for the ITU-T G.654: G.654.A, G.654.B, G.654.C and G.654.D, where they are distinguished by their PMD requirements, Mode Field Diameter (MFD)requirements and chromatic dispersion coefficients.[8]

3.2.3.1 *G.654.A*

The ITU-T G.654.A is the base category for the cut-off shifted singlemode optical fiber and cable. Table 14 shows this category has a very low attenuation, thereby suited for long-distance digital transmission applications, such as long-haul terrestrial line systems and submarine cable systems using optical amplifier. Recommended by ITU-T for use in systems such as ITU-T G.691, G.692, G.957 and G.977 in the 1550 nm wavelength region.[22]

G.654.A		
Attribute	Description	Value
MFD	Range of nominal values	9.5-10.5 µm
Attenuation coefficient	Max at 1550 nm	0.22 dB/km
PMD coefficient	Max PMD_Q	$0.5\ \text{ps}/\sqrt{\text{km}}$
See appendix for the rest of the attributes		

Table 14: G.654.A fiber attributes[8]

3.2.3.2 *G.654.B*

Table 15 shows category G.654.B has a larger upper MFD value of 13 µm than 10.5 µm of category G.654.A, and a reduce PMD requirements of $0.2\ \text{ps}/\sqrt{\text{km}}$ compared to category G.654.A with $0.5\ \text{ps}/\sqrt{\text{km}}$. This reduction allows G.654.B to have a higher bit rate capacity, suited for higher data rate communications. This category is suited for the same ITU-T systems as category G.654.A and for ITU-T G.69.1 long-haul applications in the 1550 nm region. The Recommendation ITU-T G.973 also specifies that G.654.B can be applied for longer distance and larger capacity Wavelength Division Multiplexing (WDM) repeaterless submarine systems with remotely pumped optical amplifer. Recommendation G.977 also specifies the use for G.654.B with submarines systems with optical amplifier.

3.2.3.3 *G.654.C*

ITU-T G.654.C attributes is similar to the G.654.A, except on the PMD requirements where its identical to the G.654.B, with 0.2

G.654.B		
Attribute	Description	Value
MFD	Range of nominal values	9.5-13 µm
Attenuation coefficient	Max at 1550 nm	0.35 dB/km
PMD coefficient	Max PMD_Q	$0.2\ \text{ps}/\sqrt{\text{km}}$
See appendix for the rest of the attributes		

Table 15: G.654.B fiber attributes[8]

$\text{ps}/\sqrt{\text{km}}$ shows in table 16. Enabling it suitable for higher bit rate and long-haul applications, such as those discussed in Recommendation ITU-T G.959.1.[22]

G.654.C		
Attribute	Description	Value
MFD	Range of nominal values	9.5-10.5 µm
Attenuation coefficient	Max at 1550 nm	0.35 dB/km
PMD coefficient	Max PMD_Q	$0.2\ \text{ps}/\sqrt{\text{km}}$
See appendix for the rest of the attributes		

Table 16: G.654.C fiber attributes[8]

3.2.3.4 *G.654.D*

This category has attributes similar to the G.654.B, but have a higher value of lower and upper limit to the MFD value than all of the other G.654 categories, to improve on the Optical Signal to Noise Ratio (OSNR) characteristics. Table 17 it has also a modified macrobend loss and lower attenuation coefficient of 0.20 dB/km, compared to 0.22 dB/km of the other categories. This Recommendation is suiteable for higher bit-rate submarine systems described in the ITU-T G.973, G.973.1, G.973.2 and G.977.[22]

G.654.D		
Attribute	Description	Value
MFD	Range of nominal values	11.5-15 µm
Attenuation coefficient	Max at 1550 nm	0.20 dB/km
PMD coefficient	Max $\mathrm{PMD_Q}$	$0.20\ \mathrm{ps}/\sqrt{\mathrm{km}}$
See appendix for the rest of the attributes		

Table 17: G.654.D fiber attributes[8]

3.2.3.5 *Review of the Recommendation G.654*

Table 18 summarize the categories of the ITU-T G.654.

G.654			
	Characteristics	Wavelength Coverage	Applications
G.654.A	Maximum attenuation of 0.22 dB/km at 1550 nm. Max $\mathrm{PMD_Q}$=$0.5\ \mathrm{ps}/\sqrt{\mathrm{km}}$	1550 nm	Suited for long-distance digital transmission applications, such as long-haul terrestrial line systems and submarine cable systems using optical amplifier
G.654.B	Maximum attenuation of 0.22 dB/km at 1550 nm. Max $\mathrm{PMD_Q}$=$0.20\ \mathrm{ps}/\sqrt{\mathrm{km}}$	1550 nm	Same ITU-T system as G.654 .A and for ITU-T G.69.1 long-haul applications in the 1550 nm region. Also suited for longer distance and larger WDM repeaterless submarine systems with remotely pumped opical amplifier in G.973. Also for submarine systems with optical amlifier in G.977
G.654.C	Maximum attenuation of 0.22 dB/km at 1550 nm. Max $\mathrm{PMD_Q}$=$0.20\ \mathrm{ps}/\sqrt{\mathrm{km}}$	1550 nm	Suited for higher bit-rate and long-haul applications in G.959.1
G.654.D	Maximum attenuation of 0.20 dB/km at 1550 nm. Max $\mathrm{PMD_Q}$=$0.20\ \mathrm{ps}/\sqrt{\mathrm{km}}$	1550 nm	Suited for higher bit-rate submarine systems in G.973, G.973.1, G.973.2 and G.977

Table 18: G.654: Characteristics of a cut-off shifted singlemode optical fibre and cable[20]

3.2.4 *G.655 Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable*

As WDM techniques became more popular to use in optical fiber communications, along with it comes problems such as dispersion. When multiple optical channels pass through the same fiber, zero dispersion at 1550 nm is the biggest problem that arise, due to nonlinear optical interactions among WDM channels such as FWM and Cross Phase Modulation (CPM). The signal degradation is so severe that zero-dispersion shifted fiber such as the G.653 becomes unusable for DWDM systems. A new fiber to overcome this problem is then needed to be developed, the way to avoid FWM is to move the zero-dispersion wavelength outside the transmission band. A new type of dispersion controlled fiber, the Non-Zero Dispersion Shifted Fiber (NZ-DSF) was invented, by using other layered core structures to adjust the amount of waveguide dispersion differently.[27][17]

The ITU-T Recommendation G.655 NZ-DSF, describes a singlemode fiber with a chromatic dispersion coefficient that is greater than some non-zero value throughout the wavelength range from 1530 nm. This dispersion helps reduced the growth of nonlinear effects that can arise in DWDM systems. This dispersion can be provided by moving the zero-dispersion wavelength either above(at shorter wavelengths) or below(at longer wavelengths) the 1550 nm band.[17][4]

With the latest revision of this Recommendation there exist now five categories: G.655.A, G.655.B, G.655.C, G.655.D and G.655.E. These fibers were originally intended for use at wavelengths in the range of 1530 to 1565 nm, but provisions can be made to support at wavelengths up to 1625 nm and down to 1460 nm. These categories are largely distinguished by their PMD and chromatic dispersion requirements.[4]

3.2.4.1 *G.655.A*

Recommendation G.655.A is the earliest category that was released and dedicated to operate in the C band, where the chromatic dispersion lies in the range of 0.1 to 6 ps/(nm×km) for the spectral range of 1530 to 1565 nm, seen in table 19. Its attenuation coefficient is defined only for the C band and is lower than 0.35 dB/km at 1550 nm. The PMD_Q is identical to the G.652.A, which is a conventional singlemode fiber. The G.652.A has recommended attributes and values to support applications such as the ITU-T G.691, G.692 and G.659.1. Concerning G.692(DWDM transmission) applications, depending on channel wavelength and dispersion characteristics of the fiber, the maximum total power could be restricted, and the minimum channel spacing could be restricted to 200 GHz.[27][1]

G.655.A		
Attribute	Description	Value
CD coefficient	λ_{min} and λ_{max}	1530 and 1565 nm
	Min value of D_{min}	0.1 ps/(nm×km)
	Max value of D_{max}	6 ps/(nm×km)
Attenuation coefficient	Max at 1550 nm	0.35 dB/km
PMD coefficient	Max PMD_Q	0.2 ps/$\sqrt{\text{km}}$
See appendix for the rest of the attributes		

Table 19: G.655.A fiber attributes[1]

3.2.4.2 *G.655.B*

The G.655.B has extended its operation window to cover C and L band, where its attenuation coefficient are defined to be lower than 0.4 dB at 1625 nm and 0.35 dB at 1550 nm, table 20 shows. The permitting chromatic dispersion has been increased to adopt even faster data rate and narrower channel spacing, where it lies at 1 to 10 ps/(nm×km). Its PMD requirement is also increased to 0.5 ps/$\sqrt{\text{km}}$, compared to the G.655.A with 0.2 ps/$\sqrt{\text{km}}$, decreasing its transmission capacity. The G.655.B is suitable for applications such as ITU-T G.691, G.692, G.693 and G.659.1. The same as G.655.A, concerning G.692 applications, depending on channel wavelengths and dispersion characteristics of the fiber, the launch power for fiber can be higher, and the minimum channel spacing could be 100 GHz or less. Also the PMD requirement allows operation of STM-64 systems to at least 400 km in length.[27][1]

3.2.4.3 *G.655.C*

The G.655.C is almost identical to the G.655.B, except for its PMD requirements. the PMD requirements has been reduced from 0.5 to 0.2 ps/$\sqrt{\text{km}}$, seen in table 21, to increase transmission capacity,. G.655.C attributes, retains it original specification for the dispersion coefficent, which allows a reference to negative dispersion fibers that may be suitable as part of dispersion managed links such as those used in submarine systems. Its

G.655.B		
Attribute	Description	Value
CD coefficient	λ_{min} and λ_{max}	1530 and 1565 nm
	Min value of D_{min}	1.0 ps/(nm×km)
	Max value of D_{max}	10 ps/(nm×km)
Attenuation coefficient	Max at 1550 nm	0.35 dB/km
	Max at 1625 nm	0.4 dB/km
PMD coefficient	Max PMD_Q	0.5 ps/$\sqrt{km}$
See appendix for the rest of the attributes		

Table 20: G.655.B fiber attributes[1]

attributes and values also allows for support for optical interface Recommendations such as the ITU-T G.691, G.659.1 and G.693. For DWDM systems, depending on the minimum dispersion that is selected, it could support channel spacing defined in G.694.1. The PMD requirement allows for operation of STM-64(10 Gbps) systems to lengths up to 2000 km, depending on other systems, and for G.659.1 STM-256(40 Gbps) application.[27][4]

G.655.C		
Attribute	Description	Value
CD coefficient	λ_{min} and λ_{max}	1530 and 1565 nm
	Min value of D_{min}	1.0 ps/(nm×km)
	Max value of D_{max}	10 ps/(nm×km)
Attenuation coefficient	Max at 1550 nm	0.35 dB/km
	Max at 1625 nm	0.4 dB/km
PMD coefficient	Max PMD_Q	0.2 ps/$\sqrt{km}$
See appendix for the rest of the attributes		

Table 21: G.655.C fiber attributes[4]

3.2.4.4 *G.655.D*

The G.655.D defines the chromatic dispersion coefficient as a pair of bounding curves versus wavelength for wavelengths in the range of 1460 to 1625 nm, seen in table 22. For wavelengths greater than 1530 nm, the dispersion is positive and sufficient enough in magnitude to suppress most nonlinear impairments. For wavelengths less than 1530 nm, the dispersion crosses zero, but can be used to support CWDM applications at channels from 1471 nm and higher.[4]

G.655.D		
Attribute	Description	Value
CD coefficient	$D_{min}(\lambda)$:1460-1550 nm	$\frac{7.0}{90}(\lambda - 1460) - 4.20$
(ps/nm×km)	$D_{min}(\lambda)$:1550-1625 nm	$\frac{2.97}{75}(\lambda - 1550) + 2.80$
	$D_{max}(\lambda)$:1460-1550 nm	$\frac{2.91}{90}(\lambda - 1460) + 3.29$
	$D_{max}(\lambda)$:1550-1625 nm	$\frac{5.06}{75}(\lambda - 1550) + 6.20$
Attenuation coefficient	Max at 1550 nm	0.35 dB/km
	Max at 1625 nm	0.4 dB/km
PMD coefficient	Max PMD_Q	0.2 ps/$\sqrt{km}$
See appendix for the rest of the attributes		

Table 22: G.655.D fiber attributes[4]

3.2.4.5 *G.655.E*

The G.655.E has the same chromatic dispersion coefficient style as the G.655.D, table 23 shows, but has higher values that can prove useful for certain systems, for example those with smallest channel spacing. It supports the same systems as the G.655.D.[4]

G.655.E		
Attribute	Description	Value
CD coefficient	$D_{min}(\lambda)$:1460-1550 nm	$\frac{5.42}{90}(\lambda - 1460) + 0.64$
(ps/nm×km)	$D_{min}(\lambda)$:1550-1625 nm	$\frac{3.30}{75}(\lambda - 1550) + 6.06$
	$D_{max}(\lambda)$:1460-1550 nm	$\frac{4.65}{90}(\lambda - 1460) + 4.66$
	$D_{max}(\lambda)$:1550-1625 nm	$\frac{4.12}{75}(\lambda - 1550) + 9.31$
Attenuation coefficient	Max at 1550 nm	0.35 dB/km
	Max at 1625 nm	0.4 dB/km
PMD coefficient	Max PMD_Q	0.2 ps/$\sqrt{km}$
See appendix for the rest of the attributes		

Table 23: G.655.E fiber attributes[4]

3.2.4.6 *Review of the Recommendation G.655*

Table 24 summarize the categories of the ITU-T G.655.

3.2.5 *G.656 Characteristics of a fibre and cable with non-zero dispersion for wideband optical transport*

This ITU-T Recommendation G.656 has characteristics of a fiber and cable with non-zero dispersion for wideband transport.

G.655			
	Characteristics	Wavelength Coverage	Applications
G.655.A	Maximum attenuation at 1550 nm only. Lower CD value than B and C category. Max PMD_Q=0.5 $ps/\sqrt{km}$	C band	Support DWDM transmission(G.692) applications in the C band with down to 200 Ghz channel spacing.
G.655.B	Maximum attenuation specified at 1550 and 1625 nm. Max PMD_Q=0.5 $ps/\sqrt{km}$	C+L band	Support DWDM transmission(G.692) applications in the C+L band with down to 100 GHz channel spacing.
G.655.C	Maximum attenuation specified at 1550 and 1625 nm. Max PMD_Q=0.2 $ps/\sqrt{km}$	O to C band	Similar to G.655.B, but allows for transmission applications at high bit rates for STM-64(10 Gbps) up to 2000 km. Also suitable for STM-256(40 Gbps)
G.655.D	Maximum attenuation specified at 1550 and 1625 nm. Max PMD_Q=0.2 $ps/\sqrt{km}$	C+L band	For wavelengths greater than 1530 nm, Similar applications to G.655.B are supported. For wavelength less than 1530 nm, can support CWDM applications at channels 1471 nm and higher.
G.655.E	Maximum attenuation specified at 1550 and 1625 nm. Max PMD_Q=0.2 $ps/\sqrt{km}$	C+L band	Similar to G.655.D, but have higher CD values for applications with small channel spacing.

Table 24: G.655: Charateristics of non-zero dispersion shifted singlemode optical fiber and cable[20]

The chromatic dispersion value is greater than some non-zero value throughout the wavelength range of 1460 to 1625 nm. This dispersion helps reduce the growth of nonlinear effects which is a problem with DWDM systems. Similar to the Recommendation G.655.E, which expanded the window to S+C+L band, by expanding the window, the dispersion at the long wavelength boundary increased to ≈14 ps/(nm×km), which significantly reduces FWM and CPM among WDM channels. The expansion of operating window, is a direction taken to increase capacity transmitted on an optical fiber, making this type of fiber that could be utilize for both CWDM and DWDM systems through the wavelength range from 1460 to 1625 nm.[27][7]

Table 25 shows the G.656 has only one category and defines the chromatic dispersion coefficient as a pair of bounding curves versus wavelength for wavelength from 1460 to 1625 nm. Furthermore its attenuation coefficient is identical to the other NZ-DSF categories, except the G.656 has added another maximum at 1460 nm with 0.4 dB/km. The PMD requirement is the identical to other NZ-DSF with the lowest value recommended of 0.2 ps/$\sqrt{\text{km}}$.[22]

The Recommendation G.656 has attributes that intended for supporting of CWDM applications as those describe in Recommendation G.695 and also DWDM applications such as the ITU-T G.691, G.692, G.693, G.696.1, G.698.2 and G.659.1. The G.694.1 DWDM systems and with specified channel spacing, are supported, depending on the minimum dispersion that is selected. The PMD requirement allows operation for systems such as STM-64 up to 2000 km in lengts, depending on system elements.[22][7]

G.656		
Attribute	Description	Value
CD coefficient	$D_{min}(\lambda)$:1460-1550 nm	$\frac{2.60}{90}(\lambda - 1460) + 1.00$
(ps/nm×km)	$D_{min}(\lambda)$:1550-1625 nm	$\frac{0.98}{75}(\lambda - 1550) + 3.60$
	$D_{max}(\lambda)$:1460-1550 nm	$\frac{4.68}{90}(\lambda - 1460) + 4.60$
	$D_{max}(\lambda)$:1550-1625 nm	$\frac{4.72}{75}(\lambda - 1550) + 9.28$
Attenuation coefficient	Max at 1460 nm	0.4 dB/km
	Max at 1550 nm	0.35 dB/km
	Max at 1625 nm	0.40 dB/km
PMD coefficient	Max PMD_Q	0.2 ps/$\sqrt{\text{km}}$
See appendix for the rest of the attributes		

Table 25: G.656 fiber attributes[4]

3.2.5.1 *Review of the Recommendation G.656*

Table 26 summarize the categories of the ITU-T G.656.

G.656			
	Characteristics	Wavelength Coverage	Applications
G.656	Maximum attenuation at 1460, 1550 and 1625 nm. Max PMD_Q=0.2 ps/$\sqrt{\text{km}}$	S, C and L band	Supports both CWDM and DWDM systems throughot the wavelength range of 1460 to 1625 nm.

Table 26: G.656: Charateristics of non-zero dispersion shifted fiber for wideband transport[20]

3.2.6 *G.657 Characteristics of a bending-loss insensitive single-mode optical fibre and cable for the access network*

The lastest revisions of the Recommendation G.657 approved in 2012 is restricted from public access, thereby part of this sections information comes from other sources and from ITU-T 2009 revision.[22]

The ITU-T Recommendation G.657 specifies the characteristics of a bending loss insensitive singlemode optical fiber and cable for access network and is the latest edition among the singlemode optical fiber standards. This bend insensitive fiber is to provide nominal specification for the Fiber to the Home (FTTH) markets, where sharp bends are unavoidable in FTTH deployment. In the FTTH environment, the limited space, dense distribution and short lengths of drop cables are used to connect to customer premises, will inevitably introduce macrobending of optical fiber with small radius, which result in large bending loss in conventional singlemode fibers. Similar to the multimode Recommendation G.651.1, the singlemode G.657 bend insensitive fibers are attractive for FTTH, because it lowers installation costs and improve system performance.[27][22]

The improved macrobending behaviour of the Recommendation G.657 supports for use in broadband optical access networks, supports small volume fiber management systems and low radius mounting in telecom offices and customer premises in apartment buildings and single dwelling houses.[22]

There exist two categories of the ITU-T Recommendation G.657: G.657.A and G.657.B. The purpose of introducing these two categories was to provide strongly improved bending performance compared to the existing Recommendation ITU-T G.652.

3.2.6.1 *G.657.A*

Category G.657.A is compliant with the existing ITU-T G.652.D and have the same transmission and interconnection properties. The main improvement from G.652.D are its lower bending loss and tighter dimensional specifications, both for improved connectivity. The category is also suited for operation in the band of O, E, S, C and L, throughout the wavelength range of 1260 to 1625 nm. The Category G.657.A have two sub-categories, named G.657.A1 and G.657.A2 fibers. They are distinguished by their macrobend loss, as seen in table 27, except from this difference their attributes are identical. Category A1 has a smaller macrobend loss at 10 and 15 mm than category A2, but A2 has in addition a lower bend radius at 7.5 mm. Its PMD requirements of 0.20 $\mathrm{ps}/\sqrt{\mathrm{km}}$ is of the lowest recommended by ITU-T, for enhance transmission capacity and ensure longer link distance communications. The Category G.657.A support optimized access network installation with respect to macrobending loss.[22][5][12]

G.657.A						
Attribute	Description	Value				
		G.657.A1		G.657.A2		
Macrobend Loss	Radius(mm)	15	10	15	10	7.5
	Number of turns	10	1	10	1	1
	Max at 1550 nm(dB)	0.25	0.75	0.03	0.1	0.5
	Max at 1625 nm(dB)	1.0	1.5	0.1	0.2	1.0
Attenuation coefficient	Max from 1310 nm to 1625 nm	0.4 dB/km				
	Max at 1383 nm ± 3 nm	0.4 dB/km				
	Max at 1550 nm	0.3 dB/km				
PMD coefficient	Max PMD_Q	0.20 $\mathrm{ps}/\sqrt{\mathrm{km}}$				
See appendix for the rest of the attributes						

Table 27: G.657.A fiber attributes[5]

3.2.6.2 *G.657.B*

Category G.657.B does not need to be compliant with ITU-T G.652, but have a very low values of macrobend loss at very low bend radii and is predominantly intended for use inside buildings. These fibers have different splicing and connection properties than ITU-T G.652, but have an even lower bending radii than G.657.A because of the further improved bending loss. This class of fiber are suitable for transmission at 1310, 1550 and 1625 nm for restricted distances that are associated with in-building transport of signals. The category G.657.B has two sub-categories: category B2 and B3, distinguished by their macrobending requirements. Category B2 have requirements for higher macrobend radii and loss than category B3, seen in table 28. The PMD requirements and chromatic dispersion coefficients are not necessary because Category B fiber supports a part of optimized access network installation with very small bending radii. The category supports optimized access network installation with very small bending radii applied in fiber management systems and particularly for restricted distance installations.[5][22][12]

G.657.B							
Attribute	Description	Value					
		G.657.B2			G.657.B3		
Macrobend Loss	Radius(mm)	15	10	7.5	10	7.5	5
	Number of turns	10	1	1	1	1	1
	Max at 1550 nm(dB)	0.03	0.1	0.5	0.03	0.08	0.15
	Max at 1625 nm(dB)	0.1	0.2	1.0	0.1	0.25	0.45
Attenuation coefficient	Max from 1310 nm	0.5 dB/km					
	Max at 1550 nm	0.3 dB/km					
	Max at 1625 nm	0.4 dB/km					
PMD coefficient	Max PMD_Q	-					
See appendix for the rest of the attributes							

Table 28: G.657.B fiber attributes[5]

3.2.6.3 *Review of the Recommendation G.657*

Table 29 summarize the categories of the ITU-T G.657

G.657			
	Characteristics	Wavelength Coverage	Applications
G.657.A	At 15 mm radius, 10 turns, 0.25 dB max at 1550 nm, 1 dB max at 1625 nm. Max PMD_Q=0.20 ps/$\sqrt{\text{km}}$	from O to L band	Optimized access installation with respect to macro bending, loss, other parameters being similar to G.652.D
G.657.B	At 15 mm radius, 10 turns, 0.03 dB max at 1550 nm, 0.1 dB max at 1625 nm	from O to L band	supports optimized access network installation with very small bending radii applied in fiber management systems and particularly for restricted distance installations

Table 29: G.657: Charateristics of non-zero dispersion shifted fiber for wideband transport[20]

3.2.7 *Comparison of Standard Optical Fibers*

Among the standard optical fibers, a few of them were designed for similar purposes, while others were for specific purposes and thereby not competing with other standards. The G.653 DSF were optimized for operation in the wavelength region between 1500 to 1600 nm, but with the introduction of WDM systems, channels near 1550 nm in DSF were seriously affected by nonlinear effect such as FWM, resulting in phasing out the G.653 for other NZ-DSF such as the G.655. The G.654 fiber were specifically developed for undersea communications, therefore does not compete with any of the other standards. Among the fibers made for WDM systems, there are the G.652.D, which is the oldest and the NZ-DSF G.655 and G.656, today some optical fiber manufacturer don't distinguished the G.655 and G.656, but rather refer them as Recommendation G.655/6 fiber. The remaining standard fibers, consist of the G.651.1 multimode fiber and the G.657 class A and B singlemode fibers, which are all bend-insensitive fibers and made for FTTH systems.

3.2.7.1 *Comparison between Optical Fibers for WDM System*

Recommendation G.652.D, G.655 and G.656 supports either CWDM or DWDM systems for long-haul transmission. The fibers have advantages and disadvantages which helps categories the fibers and distinguished them from each other. The G.652.D is a low water peak fiber with improved attenuation performance, G.655 have low chromatic dispersion and G.656 fibers have medium chromatic dispersion.[23]

The G.652.D offers attenuation from 1310 nm at 0.40 dB/km, which both the G.655/6 does not. G.655/6 were optimized for long-haul systems and therefore do not require at this low wavelength. G.655 specifies a performance at 1550 nm with 0.35 dB/km and at 1625 nm with 0.40 dB/km, the G.656 is similar to the G.655 that offers identical attenuation, except it offers and additional wavelength at 1460 nm with 0.40 dB/km. The G.652.D does not support wavelength at 1625 nm, which G.655/6 does, but it feature a reduced water absorption peak near 1383 nm, and does support the use of CWDM systemss. The G.655 were developed to support long-haul systems that use CWDM in the wavelength range from 1550 to 1625 nm. While the G.656 is optimized for long-haul system with both DWDM and CWDM systems throughout 1460 to 1625 nm.

When deploying long-haul systems over hundred of kilometers, optical signals may need to be amplified and switch along the long-haul route. These costly amplifiers and switchers are usually stored in huts that are spaced typically 75 km apart. The less attenuation a fiber has, the less huts are required, meaning the huts can be spaced further apart, which in turn reduce cost. At 1550 nm, the G.652.D offers the lowest attenuation among the compared fiber, but the G.655/6 can operate at longer wavelength.[23]

The ITU-T specifies a PMD link value of 0.20 $\mathrm{ps}/\sqrt{\mathrm{km}}$ for the G.652.D and G.655/6. This value supports 10Gb/s transmission over 1000 km, but at 40 Gb/s this same value will support less than 100 km. For long-haul a 40 Gb/s is likely for route over 40 km, using link design value less than 0.09 $\mathrm{ps}/\sqrt{\mathrm{km}}$ is recommended.[23]

Chromatic dispersion is another important factor for optimal performance in a system. The G.652.D fiber has the highest chromatic dispersion, but it also has the largest effective area. G.655 has the lowest chromatic dispersion, which results in lower systems costs for transmission at speeds less than or equal to 10 Gb/s, but at 40 Gb/s there is not enough dispersion to prevent some non-linear effects. The G.656 are a trade-off between the G.652.D and G.655.[23]

Each fibers has their weaknesses and strengths, there are simply no fiber which is best at every task. With long-haul deployment of fiber, it is not unusual to combine different fibers in the same cable, this ensures that there will be fibers optimized for every transmission strategy. It is important to look at the overall system requirements and choose the fiber which provides the most flexibility for the deployd system.[23]

3.2.7.2 *Comparison between Bend-Insensitive Fibers*

Among the standard fiber categorize as bend-insensitive fibers, are the multimode G.651.1 and the singlemode G.657.A and G.657.B fibers. These fibers are developed for use in buildings where during installation the fibers may experience sharp bends, turns, twisting and stapling of the cable. All these external condition put a lot of strain on the cable, limiting its potential.

The G.651.1 main scope is network for multi tenant buildings, while the G.657 is targeted for access network. The singlemode G.657 category A and B is distinguisable enough to be compared against each other. The G.657.A is backward compatible to the existing fiber G.652.D, and therefore can use the same transmission and interconnection properties. The G.657.B is not required to be backward compatible, but have an even better bending performance than class A.

The multimode fiber G.651.1 has the tightest bend among the multimode fibers in the market, with a bend radius at 15 mm, it has a loss of 1 dB per 2 turn at both 850 nm and 1300 nm wavelength. The G.657.A provides a roughly ten times better macrobending performance than traditional singlemode fibers, it have two sub-categories, A1 category have a better bending loss at radius 10 mm, while A2 have better bending loss at 7.5 and 15 mm. The G.657.B is truly bend-insensitive class, with hundred times better than traditional singlemode fibers and about tens times better than class G.657.A, its lowest bend radius is just at 5.0 mm. The G.657 fiber is more flexible than the multimode G.651.1, it has multiple and lower bend radius requirements and can operate at longer wavelengths. The G.657 fiber specifies a performance at the wavelength from the O to L-band, while the G.651.1 operates at wavelength at 850 and 1300 nm region.

One big factor taken into consideration when deploying fibers, is installation and deployment cost. Especially for FTTH networks and multi tenant/dwelling buildings. The advantage that G.657.A has, is backward compatibility in compliance to the older generation, which allowed for a seamless and transparent integration with existing connectorization/termination already installed. The G.651.1 and G.657.B when deployd, needs to have a full installation, thereby an increase in cost.[11]

The G.657.B with its superior bend-insensitivity, has the advantage of overcoming external stress during installation. When installing cables, one tend to use series of staples on a cable and discrete small-radius turns can affect the loss in a cable. Without a truly bend-insensitive cable, these external effects(stapling), can easily add up a couple of dB of incremental loss in a cable.[11]

The multimode G.651.1 has the advantage a multimode fiber has compared to a singlemode fiber, such as higher bit rates for short distance communications. The G.651.1 is generally not backward compatible to non-bend-insensitive multimode fiber, but by modifying the core index profile slightly to reduce the higher order modes, can make them compatible to non-bend-insensitive fiber without affecting performance of the fiber.[39]

Previously discussed in G.651.1 section, this multimode fiber functions well in enterprise networks, such as the FTTZ market, which offers significant material and electronic cost savings. In campuses and other enterprise networks or wherever the majority of network links is less than 100 or 250 m, the multimode fibers can offer a better performance than any singlemode fiber can. The G.657.A application usage lies in access networks for FTTH, especially if G.652.D spliced/connectors are already installed so G.657.A can take advantage of backward compatible. The G.657.B is primarily used for restricted distances associated with inside buildings applications, because of its short reach applications dispersion is not a concern, it has the same application usage as the G.657.A. For completely new application to be installed, one might consider using category B, because of its superior bending loss than category A, especially in multi tenant buildings where installers face tough environments where the bend diameter is very low, the G.657.B is required to overcome these problems.[9][39][11]

Part IV

NON-STANDARDS OF FIBER OPTIC SYSTEMS

4

NON-STANDARD OF FIBER OPTIC SYSTEMS

Standard optical fibers which primarily deals with communications, these optical fibers are massed produced for a continuously growing market. However, as optical fibers becomes more popular, the growing needs for special-purpose optical fibers besides communications arise. These optical fibers are developed for a niche market, and the fibers are produced in smaller quantities for applications that don't require large fiber volumes. As standard fibers are characterize and developed by organizations such as ITU-T, ISO and IEC, the non-standard fibers are typically develope by manufacturers themselves. These fibers are making inroads in fields such as industrial sensing, biomedical laser delivery systems, military gyro sensors and automative lighting and control, to name a few, but also spanned in applications as diverse as oil well downhole pressure sensors to intra-aortic catheters or high power lasers that can cut and weld steel. The requirements imposed by the variety of these applications spawns a subset of custom-tailored optical fibers, thereby given the name specialty fibers, these specialty fibers have their material and structure properties modified to render them with new properties and characteristics.[24]

Within the specialty fibers, there exist three fundamental aspects that one can engineer to develop these fibers:

- Glass composition
- Waveguide design
- Coatings

Glass composition is most basic fiber parameters and variables used for design of specialty fibers. Engineers can manipulate and change the basic structure of a fiber, by introducing a number of dopants that would act as either glass former, modifiers or actives, thus changing the fibers properties such as refractive index susceptibleor viscosity. Alternatively one can also introduce new properties such as lasing capability, fluorescence, enhanced strain or temperature sensitivity, Brillouin effect coefficient and many others.[24]

Waveguide design was one of the first design parameter exploited and led the way to define singlemode versus multimode fibers. Since its first use, waveguide design have become much more complex and has resulted in the design of specialty fibers in the range of more than one guiding core to those based on one and two dimensional photonic crystal structures.[24]

Coating is the protective parts surrounding the fiber to protect it from environmental conditions or mechanical protections and is a common feature among specialty fibers. Different circumstances require different types of coating, the wide variety of coating ranging from fibers such as high temperature polyimides to hermetic carbon coating are commercially available. However, specialty coatings can be designed with specific sensing or actuation, rather then for environmental or mechanical protection and these types of coating are beginning to be quite popular among coated fibers. These coated fibers can enhance fiber sensitivity and selectivity to a number of physical and bio-chemical measurands: i.e., humidity, specific hydrocarbons, biochemical agents, electromagnetic fields, etc.[24]

With the advantages that comes with the fields of specialty fibers, naturally there are also disadvantages. Since specialty fibers tend to be a niche market and specially designed. Volume demands are low and cost to production are high, development cost of fibers per meter to produce could be $100-1000. Therefore, end users may desist in their attempt to have custom-made fibers, unless the applications for specialty fibers has a significant market. Compared to telecommunication fiber market, the specialty fiber market is very much fragmented and much smaller in size, but its gaining traction and steadily growing in size as its popularity grows. The worldwide market of specialty fiber market was a shy boutique business in the 1990s, but grew to an impressive $239 million industry by the year 2000[24]. With continous growth it surpassed $635 million in 2010 and $673 million in 2011, and expected to reach $997 million by the year 2016[32].

4.1 DISPERSION-COMPENSATING FIBERS

In many countries, there exist a tremendous amount of fibers in underground ducts operating at 1310 nm, by upgrading these fibers to operate at 1550 nm and using optical amplifier, the transmission capacity of these fibers can be increased, but could produce significant residual positive dispersion. One method to solve the dispersion problem, is to have the zero-dispersion wavelength shifted from its natural wavelength at 1300 nm to the minimum-loss window at 1550 nm, this is the DSF. This process is done by offsetting the total chromatic dispersion in singlemode fiber which includes both waveguide dispersion and material dispersion, these dispersion can have opposite signs and thus offset each other. The zero-dispersion wavelength can be shifted so their waveguide dispersion exactly offsets their material dispersion at one wavelength, but replacing all these cables with DSF is costly and DSF is very susceptible to nonlinear effect, which was the reason it was phased out. The idea balance to avoid nonlinear effects such as FWM is to have local dispersion greater than zero, but total dispersion along a fiber route close to zero. There are ways to accomplished this, by combining different types of fiber along a route, with the dispersion of one fiber offsetting the other. For example using two or more different types of standard transmission fiber with different dispersion characteristics and combine them along the route. [17][42]

Another approach is to use the special designed fiber Dispersion Compensated Fiber (DCF), which is designed with high negative chromatic dispersion coefficient in the 1550 nm window. The DCF is designed with a small core, but have a larger refractive index between core and cladding. The purpose of this design is to create high negative material dispersion, so by combining one kilometer of DCF, one can compensate chromatic dispersion in several kilometers(typically 5 km) of singlemode fiber. To reduce the length of DCF, the negative dispersion needs to be increased, thereby reducing total length of DCF and standard fiber. The disadvantage with using DCF is because of the small core, which increases nonlinear effect, and the losses are usually higher than in standard transmission fibers.[17][42]

DCF is classified as a specialty fiber, because it is designed for a specific purpose, to balance chromatic dispersion in a transmission line. DCF are generally installed in coils at the end of a transmission line and not in cables along the route. Therefore they are regarded as a part of a transmission path, but not as part of a transmission cable. Which means that other dispersion compensating device can replace their function.[17]

4.2 HIGH-INDEX FIBER

Corning produces this type of fiber from its patented outside vapor deposition manufacturing process, with outstanding consistency and uniformity. It includes feature such as dual acrylate system that provides excellent protection from microbend-induced attenuation, excellent geometry control, high core index of refraction, efficient coupling and high NA. This fiber provides for efficient coupling whithin photonic products when used as component pigtails. Its high core index of refraction provides for a reduced bend attenuation. Its applications includes photonic products, fused fiber couplers, and EDFAs, couplers, other DWDM components and laser diode pigtails.[24]

4.3 POLARIZATION-MAINTAINING FIBER

PMF is an optical fiber that prevents light from shifting polarization just like in a radially symmetric fiber, by inducing internal stress to the fiber, thereby maintaning polarization. Polarization is the property that describes the orientation, such as time-varying direction and amplitude of the electric field vector of an electromagnetic wave.[24][17]

When polarized light travels in a conventional singlemode fiber, the state of polarization will be lost after a few meters. This polarization state can be influenced by stress within the medium it travels, and can be problematic for conventional singlemode fiber. Induced stress such as bending and twisting can change the polarization state of light in the fiber. In addition if the fiber is subjected to external disturbances, such as temperature, the output produce of polarization will vary with time, and this process holds true even on short lengths of fiber. This is an undesireable trait in many applications where a constant ouput polarization is required. A PMF with high birefringence is used to maintain polarization state, to overcome this problem.[24]

The induced internal stress can be applied by adding structures across the width within the fiber. Figure 23 shows two examples of structure design to induce internal stress: the PANDA and bowtie design, the structure is built of different types of glass. The PANDA fiber design shows two stress structure placed within the cladding in the same plane on opposite sides of the core. In the bowtie fiber design, a pair of wedges are placed on opposites sides of the core to induce stress in the fiber. Both of these designs purpose is to produce birefringences in the fiber, an asymmetric stress is applied around the core, which gives slightly different refractive indeces to two orthogonal axes. This motion of fast and slow axis will maintain the polarization state launched into the fiber over longer distances.[24][17]

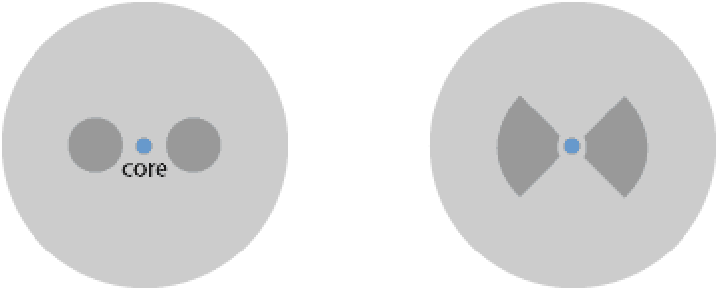

Figure 23: PMF design: PANDA(left) and bowtie(right) designs[30]

PMF main applications are in sensors and optical devices that require polarization control, such as couplers and demolators. It can also be used for high-performance transmission laser pigtails, high-data rate communications systems and applications where polarization state is to be preserved in the fiber.[24][17]

4.4 ERBIUM-DOPED FIBER

Erbium doped fibers are used in EDFA and is the most common optical amplifier. Ever since the early use of optical fibers, there has been a need for optical amplifier as an alternative technique for long distance communications. EDFA main purpose is to boost optical signals and eliminate the need for conversion of optical signals to electrical signals. The level of doping required depends on the type of amplifier. It differs from amplifiers operating at the C-band or the L-band, but it could also differ because of the power level and the number of channels being amplified. There are a number of applications utilizing a EDFA, such applications as booster amplifier for long-haul regenerated systems, power amplifiers for terrestrial and cable TV application, and small-signal amplifier in optical receivers. New-generation EDFA includes applications such as power amplifier, preamplifier, and in-line amplifier for C- and L-band.[24][17]

It's because of the properties of erbium that allows erbium fibers to assist in the regeneration of optical signals when it passes through an EDFA. The erbium ions within a doped erbium fibercan absorb light at 980 and 1480 nm and re-emit it in the 1550 nm telecommunications band through processes of pumping and stimulated emission. This enables the creation of optical amplifier that can restore power to a depleted optical signal in the 1550 nm band. In order to amplify wavelength in other regions, other chemical elements can be doped into the fiber, elements such as praseodium, thulium, ytterbium and neodymium. These other doped optical fibers have the same process of pumping and stimulated emission, but the pump and amplification wavelengths are different.[24][17]

The demand for erbium-doped amplifiers, and consequently of rare earth-doped amplifier is in high demand with the emergence of DWDM networks. In 2005 the global consumption of erbium doped fibers passed $80 million.[24]

The next-generation of optical amplifiers are optimized for operation over the entire L, S and C-band. Because erbium doped fiber does not function well in other bands, other dopants such as thulium has been explored for other wavelengths. Even so, the thulium doped fiber and other dopant are seen as less reliable than standard silica-based fiber amplifier and with material incompatibilities with installed fibers in current networks, making fusion splicing very unlikely.[24]

4.5 RAMAN FIBER

Raman fiber amplifier is fundamentally different from EDFA, it involves nonlinear effect called Raman scattering that occurs between light and atoms in the fiber medium. Raman fiber shift energy from a strong pump beam to a weaker signal. The shifting depends on the glass properties, while the wavelengths depends on the pump beam. Raman fiber amplifiers offers an improved gain over wide bandwidth by changing the pump wavelength. The Raman amplification is another variation of the phenomenon called Stimulated Raman Scattering (SRS).[24][17]

Raman amplification can function in ordinary silica fibers, and also with specialty fiber designs. The fiber does not require any special light-emitting material to be added. Although the Raman gain is low per length of fiber, the pump power must be at least several hundreds milliwats, and long lengths of fiber is required.[17]

Similar to EDFA, the Raman amplifier can simultaneously amplify many wavelengths in its operating region. The Raman gain peak is several terahertz, which is wide enough to span many optical channels in WDM systems. Raman amplifiers have low noise, but its overall gain is lower than the EDFA.[17]

As network capacity increases, high traffic amplifier such as the Raman amplifier is increasingly required.The Raman amplifier offers a solution for very broadband gain. Its main application has been in the uses of hybrid devices that both include Raman and erbium amplication stages. C-band Erbium fiber have a peak gain at the short end of their range, near 1525 nm, while Raman amplifier have a peak gain at the long end of their range. By combining these two amplifiers, to take advantage of these two gain curves together produces uniform amplification across a much wider range of wavelengths, which neither the Raman or erbium amplifier could obtain on their own. Raman amplifier has also found its place among applications, such as high-power laser diode chips and fiber-based lasers, where its claimed to provide a better power efficiency and have relative high power outputs.[24][17]

4.6 FIBER BRAGG GRATINGS AND PHOTOSENSITIVE FIBER

Photosensitive fiber is what's used to write Bragg gratings in the fibers, and FBGs quality is determined by it. Based on interferometric techniques, one can use FBG to build optical filtering functions directly into a piece of optical fiber, as seen in figure 24, and thereby increasing optical fiber transmission capacity. Higher and lower refractive indices is created in the core by exposing photosensitive fiber to UV light through a mask. The number of transmitted channels is then limited by the wavelength seperation between each Bragg grating.[24]

The core of photosensitive fiber can be created by doping it with an element, such as Germanium, this enables the core to be modulated by exposing it to a pair of interfering beams of UV light.[24]

Fiber grating functions by seperating signals at one wavelength from those at other wavelengths, by reflecting the signals it selects and sends it back in the direction it came from, as seen in figure 24.

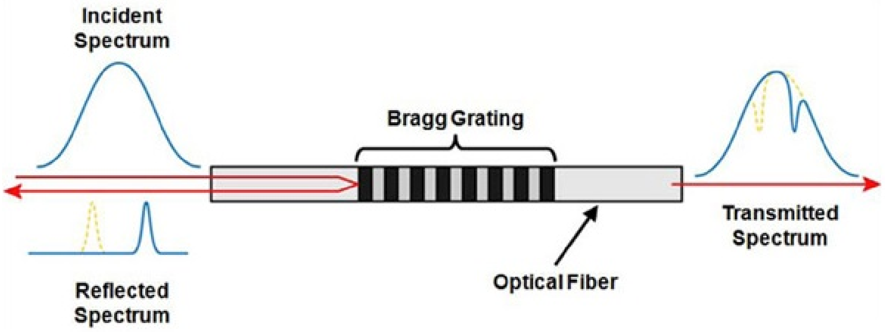

Figure 24: Illustrations of FBG in an optical fiber[34]

FBG have become an enabling technology behind DWDM. EDFA, gain-equalizing filters, WDMs, and add-drop multiplexers that was created as periodic variations in the refractive index of the core in the fiber, have helped with increasing bandwidth. FBG has also been used to fabricate optical strain and temperature sensors, with quasi-distributed measurements possible using gratings written sequentially into a continuous length of fiber.[24]

4.7 BEND-INSENSITIVE AND COUPLING FIBERS

Standard optical fibers are optimized for low attenuation transmission, but dominant loss in short lengths of fiber have arise from coupling light into the core and fiber leakages. To overcome this problem, specialty fibers with high coupling efficiency and low bend loss have been developed. These specialty fibers are used as pigtails linking light sources to fibers, given at short fiber lengths they are more efficient than standard fibers.[17]

Bend-Insensitive fibers are made by increasing the core refractive index so the core-cladding index difference is larger than in standard transmission fibers. The coupling efficiency depends on the NA, which increases the core-cladding index difference. The increase in the core-cladding difference in turn will increase the confinement angle, which will reduce light leakage at bends in the fiber. An increase in attenuation of the fiber is more than offset by the decrease in coupling and bendingloss, which is more important at short fiber segments than for regular transmission fibers.[17]

Because of their characteristics, the bend-insensitive specialty fibers are commonly used in pigtails, and also for short connections inside optical transmitters, receivers and other devices. These fibers are design flexible in which they can bend at sharp angle, thereby saving space during installation. These features are also usefull when making fused couplers, which are the most widely used type to fuse fibers together.[17]

Bend-insensitive fibers can be made for special purposes, such as a metal-clad so they can be soldered into place in optoelectronic packages, and a tapered cores so they can transfer light from a large-area source or large-core fiber into a smaller-core fiber. Others can also be made with a flattened core that can transfer light to or from planar optical waveguides more efficiently than standard fibers.[17]

4.8 REDUCED-CLADDING FIBERS

Reduced-cladding fibers have a reduction of the outer claddings diameter of 80 μm rather than the usual 125 μm. With a reduction of the cladding, it can provide higher packing density and greater flexibility than standard fibers.[17]

The standard 125 μm cladding was chosen as a means to avoid handling problem. Fibers that were smaller than 125 μm are difficult to handle and clung to the spol, fibers larger would be too stiff and could cracked when spun around a spool. Only singlemode fibers are offered with a reduce cladding diameter.[17]

This reduction in cladding can significantly reduce the volume occupied by a fiber. For example, a fiber at 80 μm without coating, has a 41 % volume of a 125 μm fiber. With a 165 μm coating, the relative volume of a reduced-cladding fiber is increased to about 44 %. The reduction of cladding does not benefit for most transmission cables, but instead would allow cables with high fiber counts to pack fibers more densely into the same volume. This is important for ribbon cables, which is packed with coated fiber cables in parallel to each other.[17]

The reduced-cladding fibers offers an increase in fiber installation flexibility, where the fiber can be bent to a radius about 40 % smaller than conventional standard fiber, or about 3 cm compared to the usual 5 cm. In practice, it's important to avoid extra attenuation from sharp bends. Tighter bend radius of reduced-cladded fiber can be important for short lengths of fiber used as pigtails or optical jumpers in package equipment.

The thinner claddings can also be an advantage when fabricating couplers.[17]

Reduce-cladding fibers as low as 65 µm cladding and 125 µm coating have been tested for a design with an increase in packaging density and reduce bend diameter. This size is at the limit of cladding design for a singlemode fiber, and pushes present fiber coating technology. This thinner coatings of fibers can be a disadvantage for the fiber, as it offers less protection for the glass and increase the risk of the coating seperating or delaminating from the cladding. These problems are important for PMF with reduced-cladding, because the external stresses transmitted through the coating and cladding onto the core can affect the polarization performance.[17]

The reduce-cladding fibers has found its uses in coiled fiber devises, where the coil of fiber occupies a large fraction of the total volume, such as fiber-optic gyroscope and optical amplifiers. The increased flexibility of the smaller fiber also allows for a tighter wind around a smaller spool.[17]

One trade-off with reduced-cladding fibers is the difficulty of handling it. Stiffness in a fiber makes it easier to handle, but the flexibility of reduce-cladding fiber increases the difficulty of handling it. Finer fibers makes it also harder to feel and to see, which pose problems for installators.[17]

4.9 OPTICAL FIBERS FOR HARSH ENVIRONMENTS

Optical fibers for harsh conditions presents unique design challenges, mainly to the coating required to maintain fiber properties. In typical harsh conditions, the fibers could be exposed to water, hydrogen, other harmful chemicals which are commonly under high pressure and temperature(> 200 °C), or where the fibers are under high stress(macrobend, microbend, etc..). These external forces have prompted in development of optical fibers with specialty designs.[21]

To face the harsh environments, optical fibers with special coatings have been developed. This type of optical fibers are usually made of a silica glass lightguide, a thin carbon coating, and a polyimide coating. The carbon layer functions like a barrier to protect from water and hydrogen fusion, thereby improving the fibers resistance to fatigue and hydrogen induced optical loss, which is common with undersea optical cables. The polyimide coating functions as an additional protection for the carbon coated fiber against mechanical damage, escpecially at elevated temperatures.[21]

For this kinds of fiber to be considered successful, meaning it have to be able to retain its characteristics, primarily its mechanical strength and waveguide properties. Which are put under stress out in the field.[21]

Typical applications where this kinds of fibers is deployd, includes monitoring of oil wells, undersea data communications, geophysical exploration, power cable temperature monitoring, fire and leak detection, and geothermal well sensing.[21]

Part V

CONCLUSION

5

CONCLUSION

Optical fibers have evolved from simply sending light through glass for a couple of meters, and at present day are able to achieve a speed of petabit per second over 50 kilometers, which was achieved by NEC and Corning in 2012 with a speed of 1.05 petabit/s(10^{15} bit/s) over 52.4 km of 12-core optical fiber[31]. Which the NEC team describe the "ultra-large capacity transmission" at 1 petabit/s, as being equal to sending 5000 HDTV videos of two hours in a single second over 50 km[31]. At present, optical fiber telecommunication have reached throughout the world[36], where Internet Service Provider (ISP) is able to provide internet access to their customer at high speed, and where undersea optical fiber cable is stretch from coast to coast. Mainstream optical fiber deployd to the home and offices around the world is thanks to the continuous work by international organizations such as ITU-T. Their standard optical fiber Recommendations G.651 to G.657 helps to unify the optical global communications system, ensuring that optical fiber equipment will function together from different manufacturer. Even in the world's fastest changing industry, ITU-T will continue to evolve and recommend fiber suited for current market needs[18]. ITU-T Recommendation for optical fiber have each been briefly overviewed in the report, mainly their characteristics and targeted applications. The Recommendations have also been compared against each other based on their targeted applications.

Optical fibers are not only viable for mainstream telecommunications, but have gradually evolved to become vital as special purpose fibers in components such as optical amplifiers, sensors, polarizers, harsh environmental applications and numerous other devices. There's a growing market for non-standardize optical fibers, fibers which have special purposes for a niche market. A substantial amount of these specialty fiber business comes from military/aerospace applications such as fiber optic gyroscopes, fiber-guided/tethered missiles, and submarine hydrophones, as well as oil and gas applications[24]. The report gives a brief overview of a small portion of the specialty fibers in existence, and primarily focused on their characteristics and targeted applications.

What was ones a simple boutique business in the 1990s, the specialty fiber business has grown tremendously over the years in the global market, in the year 2000 the business grew to a $239 million market[24]. With a dynamic growth it grew further to $635 million in 2010 and $673 million in 2011, and is expected to grow to $997 million by the year 2016[32]. Its rapid growth shows that the non-standard fiber industry has had a tremendous development, but is still not comparable to the standard fiber market.

As long as the optical fiber market keeps expanding, there will always be new development in fiber optic technology for the future needs. At present, major companies such as At&T and Verizon has begun to phase out copper wires in the telecommunication business[33], for the more reliable fiber optic technology, whether or not optical fibers will completely dominate the telecommunications industry is yet to be seen.

Part VI

APPENDIX

A

APPENDIX

A.1 STANDARD FIBER ATTRIBUTES

Fiber Attributes		
Attribute	**Description**	**G.651.1**
Cladding Diameter	Nominal (µm)	125
	Tolerance (µm)	±2
Core Diameter	Nominal (µm)	50
	Tolerance (µm)	±3
Core-cladding concentricity error	Maximum (µm)	3
Core non-circularity	Maximum (%)	6
Cladding non-circularity	Maximum (%)	2
Numerical Aperture	Nominal	0.20
	Tolerance	±0.015
Macrobend loss	Radius (mm)	15
	Number of turns	2
	Maximum at 850 nm (dB)	1
	Maximum at 130 nm (dB)	1
Proof stress	Minimum (GPa)	0.69
Modal bandwidth-length product for overfilled launch	Minimum at 850 nm (MHz·km)	500
	Minimum at 130 nm (MHz·km)	500
Chromatic dispersion coefficient	λ_{0min} (nm)	1295
	λ_{0max} (nm)	1340
	S_{0max} for $1295 \leqslant \lambda_{0min} \leqslant 1310$ nm $(ps/(nm^2 \cdot km))$	$\leqslant$0.105
	S_{0max} for $1310 \leqslant \lambda_{0min} \leqslant 1340$ nm $(ps/(nm^2 \cdot km))$	$\leqslant 375 \times (1590 - \lambda_0) \times 10^{-6}$
Cable Attributes		
Attenuation coefficient	Maximum at 850 nm (dB/km)	3.5
	Maximum at 1300 nm (dB/km)	1.0

Table 30: G.651.1 Attributes[2]

Fiber Attributes					
Attribute	**Description**	**G.652.A**	**G.652.B**	**G.652.C**	**G.652.D**
Mode field diameter	Wavelength (nm)	1310	1310	1310	1310
	Range of nominal values (µm)	8.6-9.5	8.6-9.5	8.6-9.5	8.6-9.5
	Tolerance (µm)	±0.6	±0.6	±0.6	±0.6
Cladding Diameter	Nominal (µm)	125	125	125	125
	Tolerance (µm)	±1	±1	±1	±1
Core concentricity error	Maximum (µm)	0.60	0.60	0.60	0.60
Cladding non-circularity	Maximum (%)	1	1	1	1
Cable cut-off wavelength	Maximum (nm)	1260	1260	1260	1260
Macrobend loss	Radius (mm)	30	30	30	30
	Number of turns	100	100	100	100
	Maximum at 1550 nm (dB)	0.10	-	-	-
	Maximum at 1625 nm (dB)	-	0.10	0.10	0.10
Proof stress	Minimum (GPa)	0.69	0.69	0.69	0.69
Chromatic dispersion coefficient	λ_{0min} (nm)	1300	1300	1300	1300
	λ_{0max} (nm)	1324	1324	1324	1324
	S_{0max} $(ps/nm^2 \cdot km)$	0.092	0.092	0.092	0.092
Cable Attributes					
Attenuation coefficient	Maximum at 1310 nm (dB/km)	0.50	0.40	-	-
	Maximum at 1310 to 1625 nm (dB/km)	-	-	0.40	0.40
	Maximum at 1383 nm ±3 nm (dB/km)	-	-	0.40	0.40
	Maximum at 1550 nm (dB/km)	0.40	0.35	0.30	0.30
	Maximum at 1625 nm (dB/km)	-	0.40	-	-
PMD coefficient	M (cables)	20	20	20	20
	Q (%)	0.01	0.01	0.01	0.01
	Maximum PMD_Q $(ps/\sqrt{km})$	0.50	0.20	0.50	0.20

Table 31: G.652 Attributes[3]

Fiber Attributes			
Attribute	**Description**	**G.653.A**	**G.653.B**
Mode field diameter	Wavelength (nm)	1550	1550
	Range of nominal values (µm)	7.8-8.5	7.8-8.5
	Tolerance (µm)	±0.8	±0.6
Cladding Diameter	Nominal (µm)	125	125
	Tolerance (µm)	±1	±1
Core concentricity error	Maximum (µm)	0.80	0.60
Cladding non-circularity	Maximum (%)	2	1
Cable cut-off wavelength	Maximum (nm)	1270	1270
Macrobend loss	Radius (mm)	30	30
	Number of turns	100	100
	Maximum at 1550 nm (dB)	0.50	0.10
Proof stress	Minimum (GPa)	0.69	0.69
Chromatic dispersion coefficient	λ_{min} (nm)	1525	-
	λ_{max} (nm)	1575	-
	D_{max} $(ps/(nm \cdot km))$	3.5	-
	λ_{0min} (nm)	1500	-
	λ_{0max} (nm)	1600	-
	S_{0max} $(ps/(nm^2 \cdot km))$	0.085	-
Chromatic dispersion coefficient $(ps/nm^2 \cdot km)$	$D_{min}(\lambda)$:1460-1525 nm	-	$0.085(\lambda - 1525) - 3.5$
	$D_{min}(\lambda)$:1525-1625 nm	-	$\frac{3.5}{75}(\lambda - 1600)$
	$D_{max}(\lambda)$:1460-1575 nm	-	$\frac{3.5}{75}(\lambda - 1500)$
	$D_{max}(\lambda)$:1575-1625 nm	-	$0.085(\lambda - 1575) + 3.5$
Uncabled fibre PMD coefficient	Maximum	TBD	TBD
Cable Attributes			
Attenuation coefficient	Maximum at 1550 nm (dB/km)	0.35	0.35
PMD coefficient	M (cables)	20	20
	Q (%)	0.01	0.01
	Maximum PMD_Q $(ps/\sqrt{km})$	0.50	0.20

Table 32: G.653 Attributes[6]

Fiber Attributes					
Attribute	**Description**	**G.654.A**	**G.654.B**	**G.654.C**	**G.654.D**
Mode field diameter	Wavelength (nm)	1550	1550	1550	1550
	Range of nominal values (μm)	9.5-10.5	9.5-13	9.5-10.5	11.5-15
	Tolerance (μm)	±0.7	±0.7	±0.7	±0.7
Cladding Diameter	Nominal (μm)	125	125	125	125
	Tolerance (μm)	±1	±1	±1	±1
Core concentricity error	Maximum (μm)	0.80	0.80	0.80	0.80
Cladding non-circularity	Maximum (%)	2	2	2	2
Cable cut-off wavelength	Maximum (nm)	1530	1530	1530	1530
Macrobend loss	Radius (mm)	30	30	30	30
	Number of turns	100	100	100	100
	Maximum at 1550 nm (dB)	-	-	-	TBD
	Maximum at 1625 nm (dB)	0.5	0.5	0.5	2
Proof stress	Minimum (GPa)	0.69	0.69	0.69	0.69
Chromatic dispersion coefficient	$D_{1550max}$ $(ps/(nm \cdot km))$	20	22	20	23
	$S_{1550max}$ $(ps/(nm^2 \cdot km))$	0.07	0.07	0.07	0.07
Uncabled fibre PMD coefficient	Maximum	TBD	TBD	TBD	TBD
Cable Attributes					
Attenuation coefficient	Maximum at 1550 nm (dB/km)	0.22	0.22	0.22	0.20
PMD coefficient	M (cables)	20	20	20	20
	Q (%)	0.01	0.01	0.01	0.01
	Maximum PMD_Q $(ps/\sqrt{km})$	0.50	0.20	0.20	0.20

Table 33: G.654 Attributes[8]

Fiber Attributes						
Attributen	**Description**	**G.655.A**	**G.655.B**	**G.655.C**	**G.655.D**	**G.655.e**
Mode field diameter	Wavelength (nm)	1550	1550	1550	1550	1550
	Range of nominal values (μm)	8-11	8-11	8-11	8-11	8-11
	Tolerance (μm)	±0.7	±0.7	±0.7	±0.6	±0.6
Cladding Diameter	Nominal (μm)	125	125	125	125	125
	Tolerance (μm)	±1	±1	±1	±1	±1
Core concentricity error	Maximum (μm)	0.80	0.80	0.80	0.60	0.60
Cladding non-circularity	Maximum (%)	2	2	2	1	1
Cable cut-off wavelength	Maximum (nm)	1450	1450	1450	1450	1450
Macrobend loss	Radius (mm)	30	30	30	30	30
	Number of turns	100	100	100	100	100
	Maximum at 1550 nm (dB)	0.5	-	-	-	-
	Maximum at 1625 nm (dB)	-	0.50	0.50	0.10	0.10
Proof stress	Minimum (GPa)	0.69	0.69	0.69	0.69	0.69
Chromatic dispersion coefficient wavelength range: 1530-1565 nm	λ_{min} (nm)	1530	1530	1530	-	-
	λ_{max} (nm)	1565	1565	1565	-	-
	Minimum value of D_{min} $(ps/(nm \cdot km))$	0.1	1	1	-	-
	Maximum value of D_{max} $(ps/(nm \cdot km))$	6.0	10	10	-	-
	Sign	+ or -	+ or -	+ or -	-	-
	$D_{max} - D_{min}$ $(ps/(nm \cdot km))$	-	$\leqslant 5$	$\leqslant 5$	-	-
Chromatic dispersion coefficient wavelength range: 1565-1625 nm	λ_{min} (nm)	-	TBD	TBD	-	-
	λ_{max} (nm)	-	TBD	TBD	-	-
	Minimum value of D_{min} $(ps/(nm \cdot km))$	-	TBD	TBD	-	-
	Maximum value of D_{max} $(ps/(nm \cdot km))$	-	TBD	TBD	-	-
	Sign	+ or -	+ or -	+ or -	-	-
Chromatic dispersion coefficient $(ps/nm^2 \cdot km)$	$D_{min}(\lambda)$:1460-1550 nm	-	-	-	$\frac{7.00}{90}(\lambda - 1460) - 4.20$	$\frac{5.42}{90}(\lambda - 1460) + 0.64$
	$D_{min}(\lambda)$:1550-1625 nm	-	-	-	$\frac{2.97}{75}(\lambda - 1550) + 2.80$	$\frac{3.30}{75}(\lambda - 1550) + 6.06$
	$D_{max}(\lambda)$:1460-1550 nm	-	-	-	$\frac{2.91}{90}(\lambda - 1460) + 3.29$	$\frac{4.65}{90}(\lambda - 1460) + 4.66$
	$D_{max}(\lambda)$:1550-1625 nm	-	-	-	$\frac{5.06}{75}(\lambda - 1550) + 6.20$	$\frac{4.12}{75}(\lambda - 1550) + 9.31$
Uncabled fibre PMD coefficient	Maximum	TBD	TBD	TBD	TBD	TBD
Cable Attributes						
Attenuation coefficient	Maximum at 1550 nm (dB/km)	0.35	0.35	0.35	0.35	0.35
	Maximum at 1625 nm (dB/km)	-	0.40	0.40	0.40	0.40
PMD coefficient	M (cables)	20	20	20	20	20
	Q (%)	0.01	0.01	0.01	0.01	0.01
	Maximum PMD_Q $(ps/\sqrt{km})$	0.50	0.50	0.20	0.20	0.20

Table 34: G.655 Attributes[1][4]

Fiber Attributes		
Attribute	**Description**	**G.656**
Mode field diameter	Wavelength (nm)	1550
	Range of nominal values (μm)	7-11
	Tolerance (μm)	±0.7
Cladding Diameter	Nominal (μm)	125
	Tolerance (μm)	±1
Core concentricity error	Maximum (μm)	0.80
Cladding non-circularity	Maximum (%)	2
Cable cut-off wavelength	Maximum (nm)	1450
Macrobend loss	Radius (mm)	30
	Number of turns	100
	Maximum at 1625 nm (dB)	0.50
Proof stress	Minimum (GPa)	0.69
Chromatic dispersion coefficient ($ps/nm^2 \cdot km$)	$D_{min}(\lambda)$:1460-1550 nm	$\frac{2.60}{90}(\lambda - 1460) + 1.00$
	$D_{min}(\lambda)$:1550-1625 nm	$\frac{0.98}{75}(\lambda - 1550) + 3.60$
	$D_{max}(\lambda)$:1460-1550 nm	$\frac{4.68}{90}(\lambda - 1460) + 4.60$
	$D_{max}(\lambda)$:1550-1625 nm	$\frac{4.72}{75}(\lambda - 1550) + 9.28$
Cable Attributes		
Attenuation coefficient	Maximum at 1460 nm (dB/km)	0.40
	Maximum at 1550 nm (dB/km)	0.35
	Maximum at 1625 nm (dB/km)	0.40
PMD coefficient	M (cables)	20
	Q (%)	0.01
	Maximum PMD_Q ($ps/\sqrt{km}$)	0.20

Table 35: G.656 Attributes[7]

Fiber Attributes												
Attribute	**Description**	**G.657.A**					**G.657.B**					
Mode field diameter	Wavelength (nm)	1310					1310					
	Range of nominal values (µm)	8.6-9.5					6.3-9.5					
	Tolerance (µm)	±0.4					±0.4					
Cladding Diameter	Nominal (µm)	125					125					
	Tolerance (µm)	±0.7					±0.7					
Core concentricity error	Maximum (µm)	0.50					0.50					
Cladding non-circularity	Maximum (%)	1					1					
Cable cut-off wavelength	Maximum (nm)	1260					1260					
Uncabled fiber macrobending loss		**G.657.A1**		**G.657.A2**			**G.657.B2**			**G.657.B3**		
	Radius(mm)	15	10	15	10	7.5	15	10	7.5	10	7.5	5
	Number of turns	10	1	10	1	1	10	1	1	1	1	1
	Max at 1550 nm(dB)	0.25	0.75	0.03	0.1	0.5	0.03	0.1	0.5	0.03	0.08	0.15
	Max at 1625 nm(dB)	1.0	1.5	0.1	0.2	1.0	0.1	0.2	1.0	0.1	0.25	0.45
Proof stress	Minimum (GPa)	0.69					0.69					
Chromatic dispersion coefficient	λ_{0min} (nm)	1300					TBD					
	λ_{0max} (nm)	1324										
	D_{0max} (ps/(nm$^2 \cdot$ km))	0.092										
Cable Attributes												
Attenuation coefficient	Maximum from 1310 to 1625 nm (dB/km)	0.40					-					
	Maximum from 1383 nm ±3 nm (dB/km)	0.40					-					
	Maximum at 1310 nm (dB/km)	-					0.50					
	Maximum at 1550 nm (dB/km)	0.30					0.30					
	Maximum at 1625 nm (dB/km)	-					0.40					
PMD coefficient	M (cables)	20					TBD					
	Q (%)	0.01										
	Maximum PMD_Q (ps/$\sqrt{km}$)	0.20										

Table 36: G.657 Attributes[5]

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