CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

Application on Optical Backscattering Reflectometer (OBR)

A Graduate project submitted in partial fulfillment

of the requirements for the degree of Master of Science

in Electrical Engineering

By

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Abstract

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The main objective of this project is to understand the basics information on bending loss and splice loss with detail experiment on Luna instrument for a short network fiber. A historical perspective on fiber optics, fiber types, and application on fiber optics is given. An emphasis on the theoretical description for Optical Time Domain Reflectometer (OTDR) and application of the Optical Backscatter Reflectometer (OBR 4200) Luna instrument are also discussed. A demonstration of the experiment were performed on Luna Instrument 4200 series OBR by measuring length of a short network fiber, finding bending loss and using a splice in the experiment. The experiment has been done in Optiphase Lab, INC.

Chapter 1

Introduction

The technology and applications of optical fibers have progressed very rapidly in recent years. Optical fiber, being a physical medium, is subjected to perturbation of one kind or the other at all times. It therefore experiences geometrical (size, shape) and optical (refractive index, mode conversion) changes to a larger or lesser extent depending upon the nature and the magnitude of the perturbation. Fiber optics systems have allowed scientists to make many important advances in the telecommunication, mechanical and medical fields. Sound, video, and computer communications are more reliable than in the past. Engineers are able to monitor and maintain safer modes of transportation. And doctors can perform less dramatic life-improving procedures. The world of fiber optics has opened many possibilities for solving technological problems and has improved human civilization.

The business of optical fiber measuring instruments is flourishing: new instruments offering better performance and facilities are being developed all the time. Such as(OTDR) Optical Time Domain Reflectometer and (OBR) Optical Backscattering Reflectometer instruments. Chapter Two of this report gives a historical perspective on fiber optics, types and applications of optical fiber. Chapter three of this report covers bending losses and splices losses. Chapter four discusses back scattering Reflectometer and the newest instruments that are being used in the market.

Chapter five demonstrates an experiment using OBR 4200 Luna to find out the length of a short network fiber, finding bending loss as well as using a splice in the experiment. this experiment has been done by me in LAB of Optiphase, INC.

Chapter 2

Historical Perspective on Fiber Optics

Fiber optic technology is simply the use of light to transmit data. The general use of fiber Optics did not begin until the 1970s. Since that time the use of fiber optics has increased dramatically. [1]. The idea of using glass fiber to carry an optical communications signal originated with Alexander Graham Bell. However this idea had to wait some 80 years for better glasses and low-cost electronics for it to become useful in practical situations.

The real change came in the 1980s. During this decade optical communication in public communication networks developed from the status of a curiosity into being the dominant technology. Among the tens of thousands of developments and inventions that have contributed to this progress four stand out as milestones:

- The invention of the LASER (in the late 1950's)
- The development of low loss optical fiber (1970's)
- The invention of the optical fiber amplifier (1980's)
- The invention of the in-fiber Bragg grating (1990's)

The continuing development of semiconductor technology is quite fundamental but of course not specifically optical.[2]

2.1 Basics on Fiber Optics

Optical fibers are the actual media that guides the light. They can be made of glass or plastic. The plastic fibers exhibit much loss and tend to have low bandwidths so glass fibers are usually preferred. Figure 2.1 shows A typical fiber that made up of a core, cladding and a jacket, the core is the center or the actual fiber where the light propagates.

It has dimensions on the order of 5 to 600 micrometer. The cladding surrounds the core and has an index of refraction lower than that of the core, in this way the light will propagate through the core by means of total internal reflection. Surrounding the cladding is the jacket, the outer most part of the fiber. The jacket serves to protect the entire optical fiber.

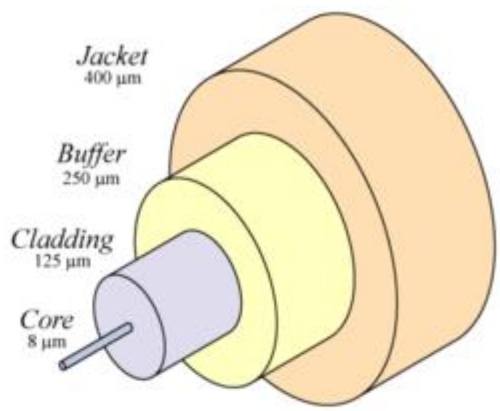

Figure 2.1: fiber optic. [3]

2.2 Types of Fiber

There are basically two types of fibers: stepped index and graded index. The stepped index fibers can be broken down into two types: single-mode and multi-mode. The stepped index fibers are fibers that have an abrupt change in refractive index from the core to the cladding while graded index fibers have a gradual change in index (Figure 2.2). The multi-mode stepped index fiber has, as one might guess, multiple paths for the light to travel while the single mode fiber only allows a single light ray to propagate.

Because the core diameter is so small, injection laser diode (ILDs) are usually used to couple light to the fiber. Multimode stepped index fibers exhibit what is referred to as modal dispersion. This is because not all the rays travel through the center of the core. Some deviate from the core and are reflected back to the center.

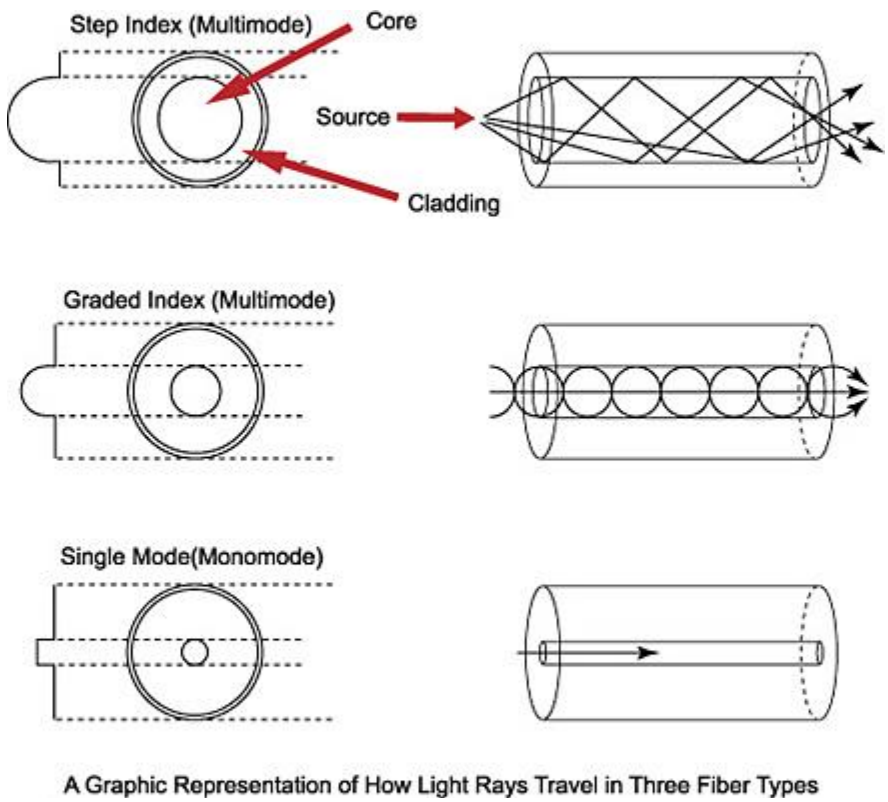

Figure 2.2 Fiber types. [3]

This reflected light takes a longer path and will therefore arrive at its destination at a later time. The graded index fibers will exhibit less of this dispersion because they gradually bend light back to the center allowing the light to travel faster when further from the core, making up for the longer distance. The single-mode stepped index fibers do not exhibit modal dispersion because of their small diameter core. Because of this they tend to have much wider bandwidths and lower losses.

In general, if the modal dispersion of a fiber is low, then the output signal will be more likely to resemble the input signal. On the other hand, if the fiber has a high modal dispersion, the output signal will actually be spread out due to the different path lengths and therefore will be less likely to resemble the input signal. When such a case is present, repeaters are needed to re-construct the signal and then send it on its way again. It is important to consider the characteristics involved when coupling a source to a fiber.

Fibers have a certain ability to collect light. This light gathering ability of the fiber is called the numerical aperture (NA). A large NA means a larger signal, or ray loss, and larger distortion "of the intelligence being thus conveyed" [4]. Also with an increase in NA comes a decrease in bandwidth. The NA is always less than 1 since it is a function of the refractive indexes of the fiber. There are four parameters that effect the efficiency of source-fiber coupling, the NAs of both the source and the fiber and the transmissions of the source and the fiber core [4].

The NA can be represented by the following equations: [2.1] and [2.2]

$$\mathrm{NA} = \sqrt{{n_1}^2 - {n_2}^2} \tag{2.1}$$

$$\mathrm{NA} = \sin\theta \tag{2.2}$$

Where n_1 is the index of the core and n_2 is the index of the cladding. θ is the half-angle of the acceptance cone of the fiber. Equation (2.1) is generally used for step-index fibers while Equation (2.2) is use for graded index fibers.

If one were given the indices of the core and cladding of a step index fiber and wanted to determine its numerical aperture the equation would break down to:

$$\theta = \sin^{-1}\sqrt{{n_1}^2 - {n_2}^2} \qquad (2.3)$$

Another important fiber parameter is transmission or power loss. Signals that travel through fibers are sometimes attenuated. This is due to a variety of things such as impurities in the fiber, scattering within the fiber (variation in the uniformity of the fiber) and micro bending [4], in which radiation escapes because of small sharp bends that may occur in the fiber.

$$P_t = P_0 e^{-\alpha L} \qquad (2.4)$$

Equation (2.4) represents the transmitted power through the fiber [1]. Where P_0 is the power into the fiber, L is the length of the fiber and α is the attenuation constant commonly referred to as fiber loss. Typical fiber loss is measured in units of decibels per kilometer (dB/km) using the relation:

$$\alpha dB = -\frac{10}{L}\, log\frac{P_t}{P_0} \qquad (2.5)$$

Where α is the loss in decibels. [4]

Fiber loss is a function of frequency so this means that fibers will have greater losses at some frequencies than others. These losses are usually specified at certain wavelengths rather than at certain frequencies. Another source of signal loss is at various locations where the light needs to re-enter or exit a fiber. These locations would include coupling to the fiber (the source end), splicing two fibers together and at the detector end of the fiber link. In order to minimize losses at these junctions, great care must be taken with the fiber. Two of the most common forms of splicing are mechanical and fusion splicing, (A detailed analysis of splice losses will be covered in chapter three) where the fibers are actually fused together.

The mechanical splice would consist of a connector matting the two ends of the fiber. Typical real world connectors cause 1 dB of loss each [4]. These losses and other characteristics of the fiber can be measured with instruments such as an Optical Power Meter or an Optical Time-Domain Reflectometer (OTDR) or optical Backscattering Reflectometer (OBR) that will be covered in chapter four. Bending loss is classified according to the bend radius of curvature: microbend loss or macrobend loss (A detailed analysis of bending losses will be covered in chapter three).

2.3 Application on Fiber Optics

Today fiber optics is used in a variety of applications from the medical environment to the broadcasting industry. It is used to transmit voice, television, images and data signals through small flexible threads of glass or plastic. These fiber optic cables far exceed the information capacity of coaxial cable or twisted wire pairs. They are also smaller and lighter in weight than conventional copper systems and are immune to electromagnetic interference and crosstalk. To date, fiber optics has found its greatest application in the telephone industry [5].

Fiber optics is also used to link computers in local area networks (LAN). It is quite apparent that fiber optics is, at the moment, an invaluable resource but the technology does have its limitations.

Fiber optics has extended its applications to sensors as well. The advantages of fiber optic sensors (FOS) in contrast to conventional electrical ones make them popular in different applications and now a day they consider as a key component in improving industrial processes, quality control systems, medical diagnostics, and preventing and controlling general process abnormalities.

Fiber optic sensors have been subject to considerable research for the past 30 years for so since they were first demonstrated about 40 years ago [2]. These new sensing technologies have formed an entirely new generation of sensors offering many important measurement opportunities and great potential for diverse applications. The most highlighted application fields of FOS are in large composite and concrete structures, the electrical power industry, Medicine, Chemical sensing, and The gas and oil industry.

Chapter 3

Bending Loss and Splice

This chapter introduces the basic information on fiber optic attenuation, and how any bending in fiber generates loss. Also in this chapter splice losses are being discussed.

3.1 Introduction

Attenuation is the loss of power in a fiber-optic cable or any optical material, and can result from many causes. During transit, light pulses lose some of their energy. Light losses occur when the fiber-optic cable are subjected to any type of stress, temperature change, or other environmental effects. The most important source of lose is the bending that occurs in the fiber-optic cable during installation or in the manufacturing process.

3.2 Light Losses in an Optical Material

When light passes through an optical component, power is lost in any optical component is dependent on the accumulative losses due to internal and external losses. Internal losses are caused by light reflection, refraction absorption, dispersion, and scattering. External losses are caused by bending, stresses, temperature changes, and overall system losses. Losses due to refraction and reflection (such as Fresnel reflection, microscopic reflection, surface reflection, and back reflection) are generally explained by the laws of light. Common losses due to absorption, dispersion, and scattering mechanisms, as well as light losses in parallel optical surfaces, and in epoxy that occur in any optical material are explained below. [6]

3.2.1 Absorption

Every optical material absorbs some of the light energy. The amount of absorption depends on the wavelength of the light and on optical material. Absorption loss depends on the physical characteristic of the optical, such as transitivity and index of refraction. The wavelength of the light passing through an optical material is a function of the index of refracting of the material.

3.2.2 Dispersion

Dispersion is caused by the expansion of light pulses as they travel through optical components. This occurs because the speed of light through the optical medium is dependent on the wavelength, the propagation mode, and the optical properties of the materials along the light path.

3.2.3 Scattering

Scattering losses occur in all optical materials. Atoms and other particles inevitably scatter some of the light that hits them. Rayleigh scattering is named after the British physicist Lord Rayleigh (1842-1919), who stated that such scattered light, is not absorbed by the particles, but simply redirected. [6]. Light scattering in the core of the fiber-optic cable is a common example, as illustrated in Figure 3.1. The further the light travels through material the more likely scattering is to occur. Rayleigh scattering depends on the type of the material and the size of the particles relative to the wavelength of the light. The amount of scattering increases quite rapidly as the wavelength decreases. scattering loss also occurs in optical material inhomogeneities introduced during glass reparation and the additional of dopants in the manufacturing process. Imperfect mixing and processing of chemicals and additives can cause inhomogeneities within the preparation of a preform. When the preform is used in the fiber-drawing method, rough areas will form in the core and thus increase the scattering of the light in the fiber.

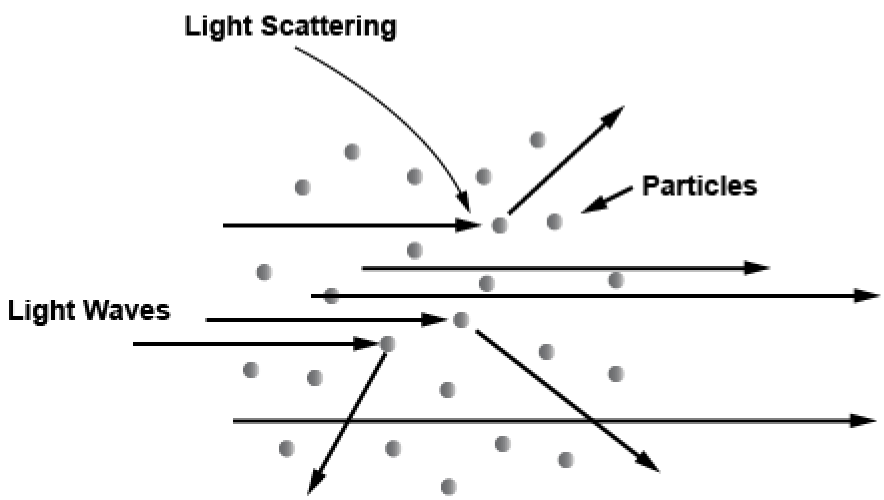

Figure 3.1 Light scattering in the fiber core. [3]

3.2.4 Light Loss in Parallel optical Surfaces

Loss of light due to reflection at a boundary between two parallel optical surfaces comprises a large portion of the total optical losses in a system. The simplest case of reflection loss occurs when an incident ray travels normal to the boundary, as shown in Figure 3.2. The reflection coefficient (ρ) is the ratio of the reflected electric field to the incident electric field. For a ray incident at the normal:

$$\rho = \frac{n_1 - n_2}{n_1 + n_2} \qquad (3.1)$$

where n_1 is the refractive index of the incident medium and n_2 is the index of the transmitted medium.

If $n_2 > n_1$, then the reflection coefficient becomes negative. This indicates a 180° phase shift between the incident and reflected electric fields. The reflectance (R) is the ratio of the reflected ray intensity to the incident ray intensity. Because the intensity in an optical beam is proportional to the square of the beam's electric field, the reflectance is equal to the square of the reflection coefficient (ρ).

The reflectance is calculated as:

$$R = \left[\frac{n_1 - n_2}{n_1 + n_2}\right]^2 \tag{3.2}$$

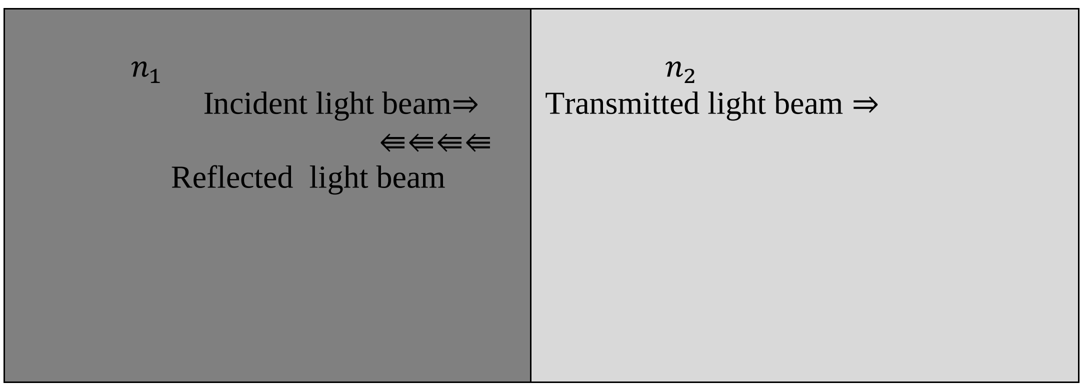

Figure 3.2 Light beam passing through media. [6]

3.2.5 Light Loss in an Epoxy Layer

Adhesives are used in manufacturing optical devices and are a key technology in the fiber-optic communications market. In order to produce low-cost and highly reliable optical components and devices, as easy-to-use, adhesive is necessary. Requirements for optical adhesive are extremely dependent upon the specific applications. These adhesives and resins are designed for a specific refractive index. They have high transmittance, precise curing time, heat-resistance, high elasticity, and permeability. [6]

Epoxy adhesives come in several forms. The most commonly used types are one-part, two-part, and UV-curable systems. One –part systems typically require heat to cure adhesive. Refrigeration of the liquid adhesive typically prolongs its shelf life. Two-part systems are based on a chemical reaction and thus must be used immediately after mixing. Setting times range from several minutes to several hours. UV-light source. As such, UV-systems do not require refrigeration. These can also be heat-treated to stabilize the cure.

3.2.6 Attenuation Calculations

Any incident light power passing through an optical component-such as glass microscope slide, fiber-optic cable, and epoxy layer-is subjected to losses. Attenuation measures the reduction in light signal strength by comparing output power with input power. Measurements are made in Decibels (dB). The decibel is an important unit of measure in fiber-optic components, devices, and systems loss calculations. [6].

$$\text{Loss(dB)} = -10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \tag{3.3}$$

Equation (3.3) is also used to calculate the loss between the input and output of the cable.

3.2.7 Bending and Micro-Bending

Any bending in a fiber-optic cable generates loss. Fiber-optic cable losses are caused by a variety of outside influences. These influences can change the physical characteristics of the cable and affect how the cable guides the light. Certain modes are affected and losses are accumulated over long distance. However, significant losses can arise from any kind of bending in a fiber cable. The cause of bending loss is easier to envisage using the ray model of light in a multimode fiber cable. When the fiber cable is straight, the ray falls within the confinement angle (θc) of the fiber cable. However as shown in figure 3.3, a bend will change the angle at which the ray hits the core-cladding interface. If the bend is sharp enough, the ray strikes the interface at an angle outside of the confinement angle, and the ray is refracted into the cladding and then to outside as loss. [6]

These are referred as leaky modes, whereby the ray leaks out and the attenuation is increased. In another class mode, called radiation mode, power from these modes radiates into the cladding and increases the attenuation. In radiation mode, the electromagnetic energy is distributed in the core and the cladding; however, the cladding carries no light.

When light is launched into a fiber cable, the power distribution varies as light propagates down the fiber cable. The power distribution decreases over long distance and eventually stabilizes. This characteristic of optical fiber is referred to as stable mode distribution. Stable mode distribution can be observed in a short fiber cables by introducing mode-filtering devices. Mode filtering may be accomplished through the use of mode scrambling, which can be achieved by bending the fiber cable to form a corrugated path. The corrugated path introduces a coupling, which leads to existence of both radiation and leaky modes. Section in chapter five experiments will show a demonstration on bending loss fiber in a short circuit.

In high-power applications, stable mode distribution can be achieved because the effective portion of the signal that “leaks” is small in comparison to the full signal strength. Mode scrambling allows repeatable laboratory measurements of signal attenuation in fiber cables. Figure 3.3 shows bend in a fiber-optical cable. Micro-bends can be a significant source of loss. When the fiber cable is installed and pressed onto an irregular surface, tiny bends can be created in the fiber cable. Light is lost due to these irregularities.

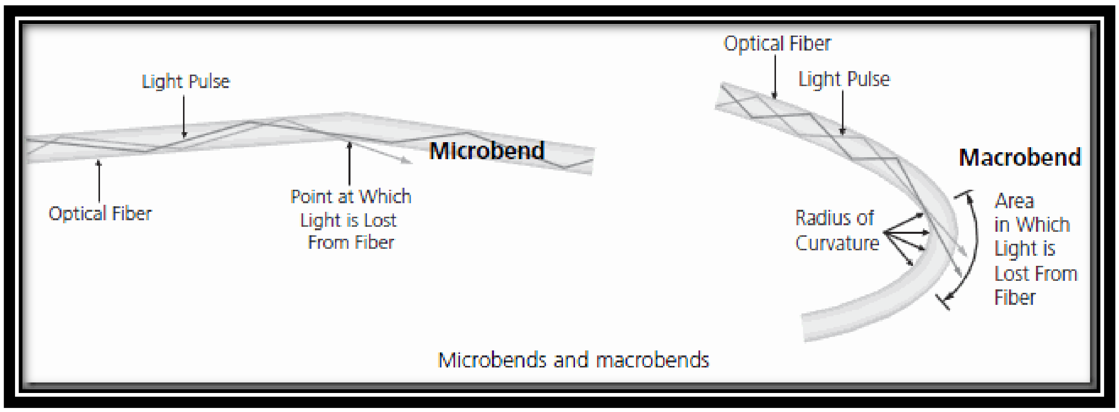

Figure 3.3 Micro-bends and Macro-bends losses. [3]

For a single-mode fiber (SMF) with length(l), bending loss (*L*) is usually obtained by [7]

$$L = 10\log_{10}(\exp(2\alpha l)) = 8.686\alpha l \qquad (3.4)$$

Where α is the bending loss coefficient, and it is a function of bending radius, wavelength of light used in the fiber, and also optical fiber structure and material of the fiber. Often when bending reaches a critical radius of curvature (R_c), then loss due to bending cannot be neglected. R_c is defined as [2]

$$R_c = \frac{3n_2 \cdot \lambda}{4\pi(NA)^3} \qquad (3.5)$$

R_c is the critical radius of bending, n_2 is the refractive index of the clad, *NA* is the numerical aperture of the fiber and λ is the wavelength.

Bending loss coefficient (2α) (dB/km), as proposed by Marcuse, is presented in equation (3.6). [7]

$$2\alpha = \sqrt{\pi}\,\delta^2 L_c \left(\frac{2n_1 ka\Delta}{bW}\right)$$

$$-\sum exp\left\{-\left[(B_g - B_{1s})\right]^2\right\} \frac{{J_1}^2\left(J_{1s}\frac{a}{b}\right)}{J_o(J_{0s})}\, exp\left(\frac{-2\alpha^2}{W^2}\right) \qquad (3.6)$$

Here 2α is the power loss in dB/length, k is the first order modified Bessel functions, a isthe radius of the fiber core, b is the propagation constant, $B_g - B_{1s}$ is the difference between the propagation constant of the straight fiber and the propagation constant of the loss modes, W is referred to as the spot size of the mode-field pattern. Equation (3.6) is considered in step index optical fibers, uses Bessel function of zero and first order (J_0, J_1) and also the root of Bessel function (J_{0s}, J_{1s}), with boundary conditions $J_0\,(J_{0s}) = 0$. $J_1(J_{1s}) = 0$. Tsao and Cheng have modified equation (3.6) for 2α, and they considered other parameters like number of wrapping turns (*N*), curve fitting function (*F*), and also *V* number. The modified equation is as follows:

$$2\alpha = 2FN\left[4\sqrt{\pi}\,\delta^2 \frac{1}{\Lambda_c}\left(\frac{n_1 k\Delta}{b}\right)^2 - \sum_8 {J_1}^2(J_{1s}\frac{b}{a})V^{-2}\right] \qquad (3.7)$$

Where Λ_c is the spatial perturbation wavelength, and is defined as

$$\Lambda_c = 2R \qquad (3.8)$$

Where R is the radius of curvature of the bend, and for loss they used the following equation:

$$L_R = \eta_{R1} exp(-\eta_{R2} \cdot R) \quad (3.9)$$

Where η_{R1}, η_{R2} are fitting parameters. Linear relationship between losses and number of turns is given by:

$$L_{N=} \eta_N \text{ . N} \quad (3.10)$$

Where L_N is the loss due to the number of wrapping turns (N). This sort of simple equation (linear) is good and valid only for larger radius of curvature, since usually for higher number of wrapping turns, saturation behavior for bending loss against (N) happens when radius of the bend is low. In most of these models one can see the effect of refractive index of the fiber (core and clad) and their differences (Δ), which are important physical parameters. Since guided mode in the fiber core can be transferred to radiation mode in the fiber cladding induced by bending, it is complicated by the explanation of simple electromagnetic effects.

3.3 Splicing

The interconnection of optical components is a vital part of an optical system, having a major effect on performance. Interconnection between two fiber-optic cables is achieved by either connectors or splices which link the ends of the fiber cables optically and mechanically. Connectors are devices used to connect a fiber device, such as a detector, optical amplifier, optical light power meter, or link to another fiber cable. They are designed to be easily and reliably connected and disconnected. The connectors create an intimate contact between the mated halves to minimize the power loss across the junction. They are appropriate for indoor applications. Splices are used permanently connect one fiber-optic cable to another. Splices are suitable for outdoor and indoor applications. Some types of splices are used to temporarily connect for quick testing purpose. This chapter covers the operating principles of the splices and describes their types, properties and operations.

Splices make optical and mechanical connections between two fiber cables. There are many applications for fiber and splices in fiber systems, such as:

- connecting between a pair of fiber cables, using a splice, is an essential part of any fiber system
- Interfacing devices to local area networks.
- Splicing may be required on short fiber cables for wiring, testing devices, connecting instruments and devices, and at other intermediate points between transmitters and receivers.

3.4 Requirements of Splices

It is very difficult to design splice that meet all the requirements. The lowest losses are desirable, but the other factors clearly influence the selection of the splice. The following is a list of the most desirable features for fiber splices required by customers and industry.

- Low loss (insertion and return). The splice cause low loss of optical power across the function between a pair of fiber cables.
- Easy installation and use. The splice should be easily and rapidly installed without the need for special tools or extensive training.
- Economical. The splice and special application tooling should be inexpensive.
- Compatibility with the environment. The splice should be water proof and not affected by temperature variation.
- Mechanical properties. The splice should have high mechanical strength and durability to withstand the application and tension forces.
- Long life. The splice should be built with material that has a long life in various applications.

3.5 Fiber Splicing

The splicing process joins fiber-optic cable ends permanently. In general, a splice has a power loss than a connector. Splices are typically used to join lengths of cable for outside applications. Splices may be incorporated into lengths of fiber-optic cable or housed in indoor/outdoor splices boxes, whereas connectors are typically found in patch panels or attached to equipment at fiber cable interfaces. There are two types of splices: mechanical and fusion. [6]

3.5.1 Mechanical Splicing

Mechanical splices join two fiber cable end together both optically and mechanically by clamping them within a common structure. In general, mechanical splicing requires less expensive equipment; however, higher consumable costs are experienced. Figure 3.4 show the sleeves splice.

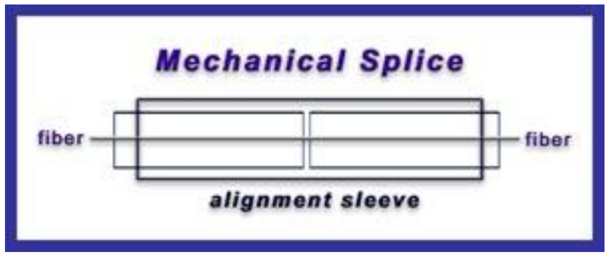

Figure 3.4 Sleeves splice. [3]

Figure 3.5 shows key-lock mechanical fiber-optic splice, commonly used to quickly mate and unmate fiber optic cables. It is made from a U-shaped metal part covered by a transparent plastic body with the two holes on each end. The prepared ends of the fiber cables are made longer than half of the length of metal power.

Figure 3.5 Key-lock mechanical fiber-optic splice. [3]

The fiber cable is inserted in center hole. When the key is inserted in the second whole towards the edge of the splice and turned by 90°, the metal part opens and one fiber cable end can be inserted. This operation can be repeated on the other side to insert the second fiber cable. This type of splice provides a quick and easy way of joining two fiber cables with low signal loss. It may be used to temporarily or permanently connect fiber cables, wavelength division multiplexing components, and other fiber-optic elements. [5]

3.5.2 Fusion Splices

Fusion splices is performed by placing the tips of the two fiber cables together by heating them by fast electrical fusion process so that they melt into one piece. Fusion splices automatically align the two fiber cable and apply a spark across the tips to fuse them. They also include instrumentation to test the splice quality and display optical parameters pertaining to the join. A fusion splice is shown in Figure 3.6. When the fusion splice is completed, a cylindrical fusion protector is placed over the splice location. Fiber fusion protectors are made from metal or polymer, and they are applied to insure mechanical strength and environmental protection. Some types of fusion splice protectors (sleeves) as sown in figure 3.7 are designed for use in place of the heat shrink method for fast, easy, and reliable permanent installation. Part of the experiment will demonstrate fiber splice and the fusion splice protector (sleeves) in chapter five. Fusion splices provide lower loss that mechanical splices. [6]

Figure 3.6 Fusion splice. [3]

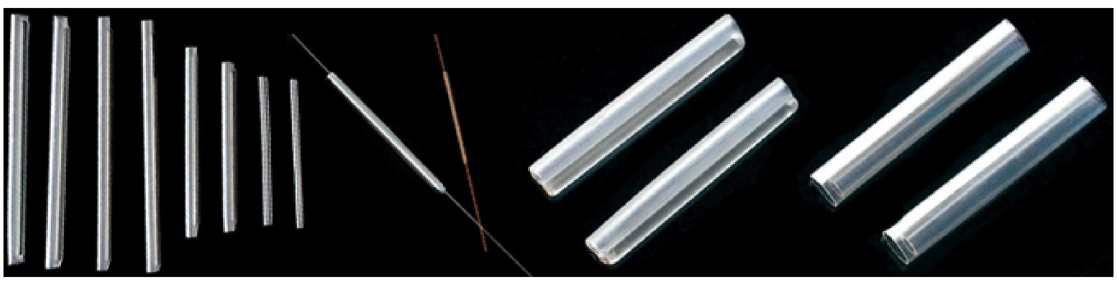

Figure 3.7 Fusion splice protector (sleeves). [3]

Some mechanical and fusion splices are used with one of splice closure. Figure 3.8 Shows splice closures. Splice closures are standard pieces of hardware in the telecommunication industry for protecting fiber-optic cable splices. Splices are protected mechanically and environmentally within the sealed closure. Splice closures are waterproof.

Figure 3.8 Splice closure. [3]

Water is kept out by using non-flowing gel under permanent compression. They are suitable for indoor, outdoor, and underground cable system installations. There are small and large closures available for different applications.

3.6 Splice Loss

The most common misalignment at a joint between two similar fibers is the transverse misalignment similar to that shown in Figure 3.9. Corresponding to a transverse misalignment of u,(where w is referred to as the spot size of the mode-field pattern) the power loss in decibels is given by

$$\alpha(dB) \approx 4.34 \left(\frac{u}{W}\right)^2 \qquad (3.11)$$

Thus a larger value of w will lead to a greater tolerance to transverse misalignment. For W ≈ 5 μm, and a transverse offset of 1 μm, the loss at the joint will be approximately 0.18 dB. On the other hand, for W ≈ 3 μm, a transverse offset of 1 μm will result in a loss of about 0.5 dB.

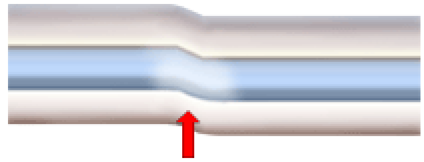

Figure 3.9 Splice misalignment. [3]

An Optical Time Domain Reflectometer (OTDR) can be used for splice loss measurement. A cable section-containing splices are normally shown as knees on the optical power loss OTDR graph. Splice loss measurements with an OTDR must be conducted from both directions and averaged (by adding with signs) for accurate splice loss. It is important to remember that actual splice-loss is the measured splice-loss in both directions divided with two.

Example:

Splice Loss = [Splice loss A to B + Splice loss B to A] / 2

Splice loss dependent on how accurately the fiber ends are aligned during splicing and Mode Field Diameter (MFD) of the two fibers. More splice loss can be observed for misalignment of the fibers and higher difference in MFD values. The MFD is a characteristic, which describes the mode field (cross-sectional area of light) traveling down a fiber at a given wavelength. When fibers with different MFD values are spliced together, a MFD mismatch occurs at splice point. With the help of the following formula splice loss due to MFD mismatch can be calculated from MFDs (in µm) of two fibers.

Splice Loss (in dB) = 20 Log 1/2 [(MFD1/MFD2) + (MFD2/MFD1)]

As an application for bending losses and splice losses, The OBR 4200 instrument (newer version of OTDR) can measure fiber length, bending loss and splice loss in an accurate way, OTDR theory and BR4200 instrument will be covered in chapter four.

Chapter 4

OTDR and OBR

This chapter gives an emphasis on the theoretical description for Optical Time Domain Reflectometer (OTDR) and discusses the applications of the Optical Backscatter Reflectometer (OBR4200) Luna instrument.

4.1 Basic principles of the backscattering method

The backscattering method was invented by M. Barnoskim and M. Jensen in 1976 [8], in time when technology of the optical fiber manufacturing was at early stages. The precise and reliable measurement of local losses on the fiber was very important for further improvement of quality of fibers. The basic idea of the proposed method consisted in launching a rather short and high power optical impulse into the tested fiber and a consequent detection of back scattered optical power as a response of the fiber to the test impulse. The detected signal provides the detail picture about the local loss distribution or reflections along the fiber caused by any of the attenuation mechanisms or some other non-homogeneities on the fiber. An important feature of the method is non-destructivity and the fact that the access to only input end of the fiber is needed.

The measurement of the time delay of the detected signal from the fiber end or from any perturbation on the fiber allows to derive the information about the perturbation localization provided that the index of refraction in the fiber core or group velocity of light propagation is known. In any point on the fiber the magnitude of the backscattered optical power is proportional to the local transmitted optical power. Due to the nonzero losses this power is gradually attenuated along the fiber and consequently also the backscattered power is also attenuated. The measurement of the backscattered power as a function of time or position on the fiber gives the information about the local distribution of the attenuation coefficient along the fiber. In this way one can evaluate the space distribution and magnitude of various non-homogeneities along the fiber like optical connectors, splicing, micro- and macro-bend losses and others measurand-perturbances. The comparison of the losses closely before and after point of interest makes possible to evaluate insertion losses of the various optical components on the fiber link.

4.1.1 Theoretical description of the OTDR

The elementary experimental experience gives the relation describing the dependence of the optical power propagating along the optical fiber as a function of the distance *x*

$$P(x) = P_0 e^{-\alpha x} \cdot 1(x) \qquad (4.1)$$

Where $P(x)$ is the total optical power at the distance *x* from the point of launching the input optical impulse, P_0 is the value of the input optical power ($x = 0$), α is the total attenuation coefficient and $1(x)$ is the Heaviside step function. In practice the attenuation coefficient is usually expressed in dB/km. In this case the relation (4.1) can be rewritten into the form

$$P(x) = P_0 \cdot 10^{-\frac{\alpha' x}{10dB}} \cdot 1(x) \qquad (4.2)$$

Where α' is the total attenuation coefficient given in units dB/km. The mutual equation between α and α' is defined by

$$\alpha' = 4.35\ \alpha \qquad (4.3)$$

Total losses in the fiber are caused by different mechanisms and the total attenuation coefficient can be different at any point on the fiber. As a result it is necessary to rewrite the equation (4.1) into more general form. [9]

$$P(x) = P_0 e^{-\int_0^x \alpha(x)dx} \cdot 1(x) \qquad (4.4)$$

Where the local attenuation coefficient $\alpha(x)$ is now a function of the distance x. It be shown that the total attenuation coefficient can be roughly split into two components

$$\alpha(x) = \alpha_a(x) + \alpha_{rs}(x) \qquad (4.5)$$

Where $\alpha_a(x)$ represents the absorption losses and $\alpha_{rs}(x)$ represents the losses by Rayleigh scattering mechanism. The average value of the total attenuation coefficient $\bar{\alpha}$ (x) on the fiber section defined by distance $(0, x)$ can be calculated according to the equation [9]

$$\bar{\alpha} = \frac{1}{x} \int_0^x \alpha(x)dx \qquad (4.6)$$

The equation (4.4) can be simplified as follows

$$P(x) = P_0 e^{-\bar{\alpha}x} \cdot 1(x) \qquad (4.7)$$

The elementary optical power dP_{rs} scattered by the Rayleigh mechanism on each elementary fiber section dx (scattering center) at the distance x from the input end of the fiber is given by

$$dP_{rs}(x) = P(x) - P(x)e^{-\alpha_{rs}dx} \qquad (4.8)$$

where due to simplicity coefficient $\alpha_{rs}(x)$ was taken as constant along the fiber. Provided that $\alpha_{rs}dx$ << 1, (4.8) can be approximated by the equation

$$dP_{rs}(x) \cong P(x)\alpha_{rs}dx \qquad (4.9)$$

In accordance with the relation (4.4) the propagating local optical power $P(x)$ changes along the fiber. A part of the isotropically scattered optical power, described (4.9), is refracted at the boundary core/cladding and is totally lost and the other part is recaptured by the numerical aperture of the fiber and is directed in the forward and backward direction. The part directed backwards is called backscattered optical power.

Its magnitude is directly proportional to the backscattering coefficient (S) what allows one to express the backscattered power from the elementary section dx on the fiber in the form [10]

$$dP_{rbs}(x) = S\, dP_{rs}\,(x) = S\alpha_{rs}\left[P_0 e^{-\int_0^x \alpha(x)dx}\right]dx\ \cdot 1(x) \qquad (4.10)$$

The backscattered power is, similarly as forward propagating total optical power, attenuated on the route to the input end of the fiber. The backward attenuation coefficient (let us denote it by $\alpha''(x)$) is generally different from the forward attenuation coefficient $\alpha(x)$.

As a result one can write for the backscattered power from the elementary section dx in the point x, that can be detected at the input end of the fiber, the equation

$$dP_{rbs}(x) = S\alpha_{rs}\left[P_0\, e^{-\int_0^x [\alpha(x)+\,\alpha''(x)]dx}\right]dx\ \cdot 1(x) \qquad (4.11)$$

If one takes A_1 and A_2 as the total average attenuation coefficients at the distance x in forward and backward direction respectively and A will represent their arithmetical average A = $0.5(A_1 + A_2)$, then the equation (4.11) can be transformed into the form

$$dP_{rbs}(x) = S\alpha_{rs}P_0\, e^{-2Ax}\, dx\ \cdot 1(x) \tag{4.13}$$

For the backscattering coefficient S one can derive the analytical relation describing its magnitude for the single-mode and multi-mode fibers with a given refraction index profile. Under some simplifications a rather simple equation for the backscattering coefficient for a single-mode optical fiber can be obtained in the form. [9]

$$S = \frac{\frac{3}{2}\,(NA^2)}{\left(\frac{w_0}{\alpha}\right)^2 V^2\, n_1{}^2} \tag{4.14}$$

For the case of a multi-mode fiber with a step-index profile the backscattering coefficient can be described by

$$S_{step} = 0.38\,\frac{(NA^2)}{n_1{}^2} \tag{4.15}$$

$$S_{grad} = 0.25\,\frac{(NA^2)}{n_1{}^2} \tag{4.16}$$

where NA = $((n_1^2 - n_2^2)^{1/2}$ is the numerical aperture,n_1 , n_2 are the refractive indexes of the core and cladding respectively, w_o is the mode field diameter of the basic mode, α is the fiber core radius, V is so called normalized frequency V = $(2\pi a/\lambda)NA$.

The time dependence of the backscattered power detected at the input end of the fiber as a response to the testing impulse of the optical power. For this purpose let us consider the optical fiber into which an optical impulse of the instantaneous power P_0 and the width T_0

was coupled in the time $t = 0$. The time dependence of this impulse is given by the equation

$$P(t) = P_0[1(t) - 1(t - T_0)] \tag{4.17}$$

Where $1(t)$ is the Heaviside unit step function. One can imagine this impulse as a lit section of the fiber. The length of the region is given by $\Delta x = v_g T_0$, where v_g is the group velocity of the impulse propagation in the fiber. The position of the trailing edge of the impulse at time $(t - T_0)$ is given by x and the position of the leading edge is given by $(x + \Delta x)$. The described situation is outlined in the Figure 4.1.

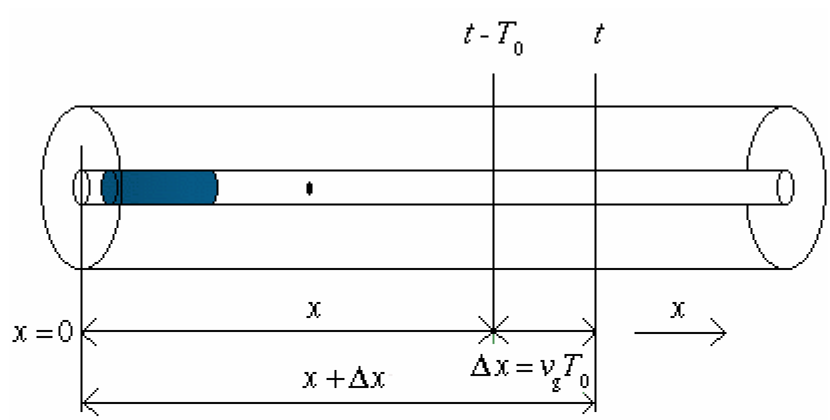

Figure 4.1 The position of the optical impulse in the fiber core at time *t*. [9]

Using the substitution $2x = v_g t$, resp. $dx = \frac{1}{2} v_g dt$, the equation (4.13) can be rewritten into the form

$$dP_{rbs}(t) = \frac{S\alpha_{rs} P_0 v_g}{2} e^{-Av_g t} dt \tag{4.18}$$

The time dependence of the backscatter power generated by the whole testing impulse can be obtained by the integration

$$dP_{rbs}(t) = \frac{S\alpha_{rs}P_0 v_g}{2} \int_{t-T_0}^{t} e^{-Av_g\tau}\, d\tau \tag{4.19}$$

Provided that $Av_gT_0 << 1$, which is for high quality fibers. Equation (4.19) can be transformed into the form

$$P_{rbs}(t) = \frac{S\alpha_{rs}P_0T_0 v_g}{2}\, e^{-Av_gt} \cdot 1(t) \tag{4.20}$$

Using the same substitution as it was done for the equation (4.18) the time dependence of the backscattered power can be described by

$$P_{rbs}(x) = \frac{S\alpha_{rs}P_0T_0 v_g}{2}\, e^{-2Ax} \cdot 1(x) \tag{4.21}$$

In the case of high quality fiber the attenuation coefficient α is given by $\alpha = A$. It makes possible to write for the backscattered power the well-known equation

$$P_{rbs}(x) = \frac{S\alpha_{rs}P_0T_0 v_g}{2}\, e^{-2\alpha x} \cdot 1(x) \tag{4.22}$$

If the fiber parameters (S, α_{rs}, α, v_g) are constant and the maximum launched power is P_0, then the maximum detectable backscattered power can be enhanced by the increase of P_0 and T_0, which define the energy of the impulse.

4.1.2 The main aspects of the signal processing in OTDR

A simplified block diagram of the OTDR-based optical reflectometer is given in the Figure 4.2. The main blocks of the reflectometer are the generator of the testing impulse and the detection system of the backscattered light. The remaining blocks provide the suitable timing of signals (clock generator) and the interpretation of the measured data (display). A 3-dB fiber power splitter makes possible to couple the optical excitation power impulse into the tested fiber and simultaneously to deviate the backscattered power to the optical receiver. [10]

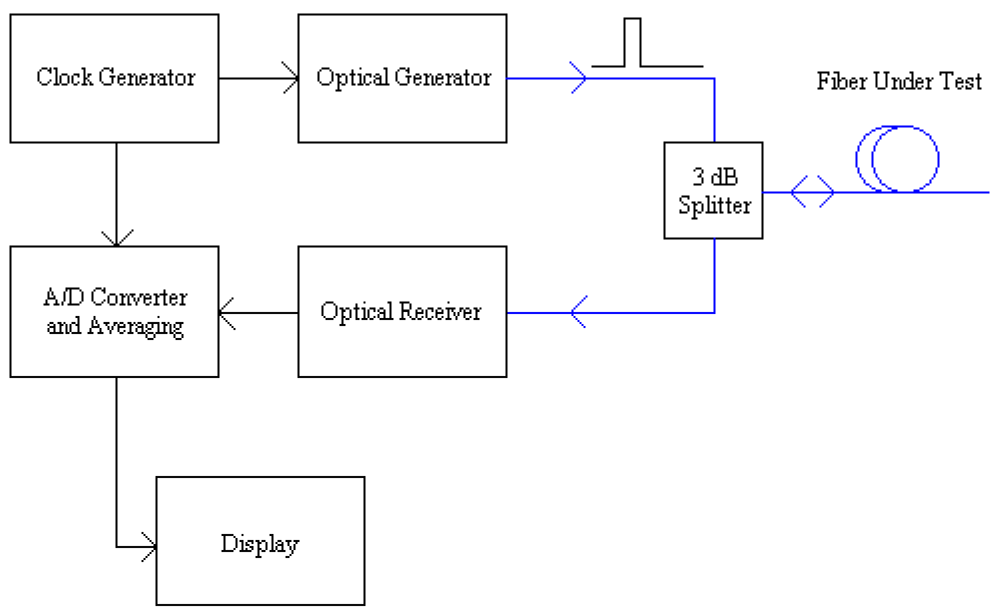

Figure 4.2. The simplified block diagram of the OTDR based reflectometer. [10]

The crucial element of the device is the block for the processing of the signal from the optical receiver. For the signal recovery a technique of signal sampling using the A/D converter simultaneously with the signal averaging method is used. For the elimination of the dead zone a blind subsidiary fiber put between the optical source and the input end of the tested fiber is used. In this way the Fresnel reflection from the input end of the tested fiber and subsequent dead zone occurs in the time corresponding to the section of subsidiary fiber and no information coming from the tested fiber is lost due to dead zone.

4.2 Overview (OBR 4200 Luna)

Luna Technologies' Optical Backscatter Reflectometer (OBR) is the industry's first ultra-high resolution OTDR with backscatter- level sensitivity designed for component- and module-level reflectometry. The OBR uses swept-wavelength coherent interferometry to measure minute reflections (< 0.0003 parts per billion) in an optical system as a function of length with spatial resolution down to 10 μm. This provides the user with unprecedented optical inspection and diagnostic capabilities. The OBR can be used to locate and troubleshoot splices, connectors, fiber bends and breaks, fiber segments, and components embedded in a short run fiber assembly. With integrated temperature and strain sensing, the OBR gives you the ultimate in fiber diagnostics. [11]

4.2.1 Measurement Performance

• -125 dB sensitivity

• 70 dB dynamic range

• Up to 500 meter length range

• 10 μm spatial resolution

• 0.05 dB loss resolution at -100 dB reflectivity

4.2.2 Application

• System design verification and analysis that can discriminate between individual devices, connectors, fibers, splices and components.

• Component qualification for inspection and rapid testing of individual optical components.

• Troubleshooting of optical systems during development and production.

• Failure analysis of devices and subassemblies.

• Distributed sensing capabilities – temperature and strain.

4.2.3Backscatter vs. Conventional Reflectometer

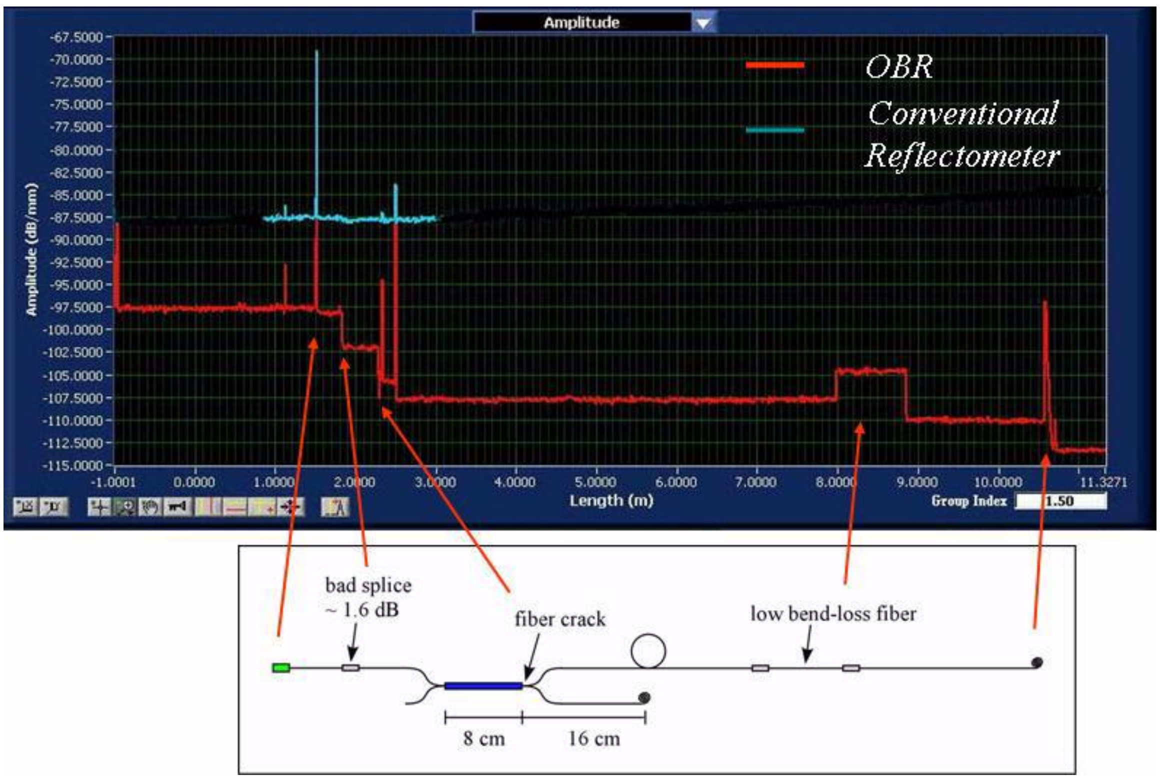

Figure 4.3. Optical Backscatter Reflectometry gives the user unprecedented visibility into optical components, assemblies, and short-haul networks. [11]

Reflectometry is based on propagating a test signal through an optical system or network and monitoring the reflected portion of that signal to get a picture of locations in the system or network that cause reflections.

Optical time-domain reflectometry (OTDR) uses short optical pulses as probes of the reflections in a network. This well-known technique is suited for measuring long network spans with relatively low resolution (meters) and medium lengths with medium resolution (centimeters).

Optical Backscatter Reflectometry is based on a frequency-domain technique, optical frequency-domain reflectometry (OFDR), that uses a tunable laser and an interferometer to probe reflections. Frequency-domain techniques are usually used to analyze systems on the component- or module-level when a very high-resolution (microns) analysis of the reflections in a system is required.

Optical backscatter reflectometry differs from other frequency-domain techniques in that it is sensitive enough to measure levels of Rayleigh backscatter in standard single-mode fiber. The figure above illustrates how this can be used to measure both reflective and non-reflective loss as light propagates down a simple optical system.

Furthermore, Luna's OBR can be used to measure the distributed spectral shift and temporal shift in the Rayleigh backscatter along an optical fiber. This capability enables distributed temperature and strain sensing with any standard telecom-grade fibers (graded index multimode as well as single mode). This technique enables robust temperature and strain measurements with high spatial resolution and accuracy. Because the measurement does not require specialty fiber, the method may be applied to existing fiber paths which were never intended to act as a sensor. This measurement capability also provides a practical and economical alternative to fiber Bragg gratings and extrinsic Fabry-Perot interferometric sensors in situations where a large number of closely spaced measurements are desired.

4.2.4 Software Features

The Luna OBR control software includes an intuitive graphical interface. All controls, options, and measurement results are easily accessible from the single main window or the menu bar.

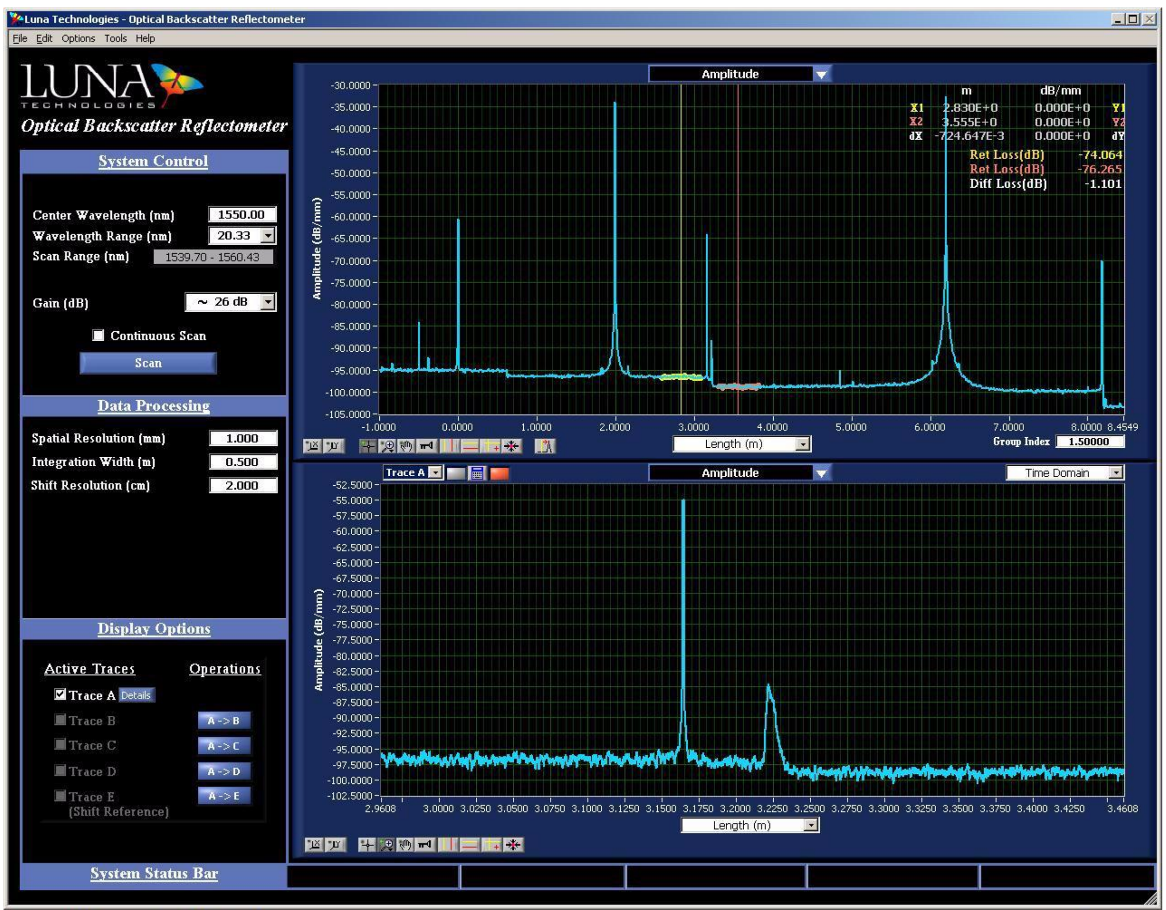

Figure 4.4 Software feature. [11]

The Luna OBR control software includes an intuitive graphical interface. All controls, options, and measurement results are easily accessible from the single main window or the menu bar.

Software features:

• System Control provides wavelength settings and scan control.

• Frequency Data Results contains a control for calculating frequency-domain data and indicators that display the current wavelength resolution and the average loss of the device under test.

• Graph Cursors display the graph coordinates for the current cursor settings. The cursors also allow the user to compare backscatter levels in different portions of the network and calculate the insertion loss between those two points in the network. The example above shows an insertion loss of 0.32 dB occurs at about 7 meters down the network under test.

• Graph Areas display measured data. The top plot is a graph of the time-domain data, and the bottom plot is a graph of time or frequency-domain data with higher resolution. Buttons on each graph control how a plot appears in the window, including multiple click and- drag zoom features as well as manual scaling options.

Because the Luna OBR measures the full scalar response of the device under test, including both amplitude and phase, it is possible to convert back and forth between time domain and frequency-domain data. The main screen displays time-domain data in the upper graph, and frequency-domain data in the lower graph. Both amplitude and phase information can be displayed in either domain. [11]

4.2.5 Time Domain

By default, the upper graph displays the amplitude of the time-domain data, which produces a plot in which each reflection within the network under test produces a peak. This provides a quick and reliable means for identifying and locating reflections within a system.

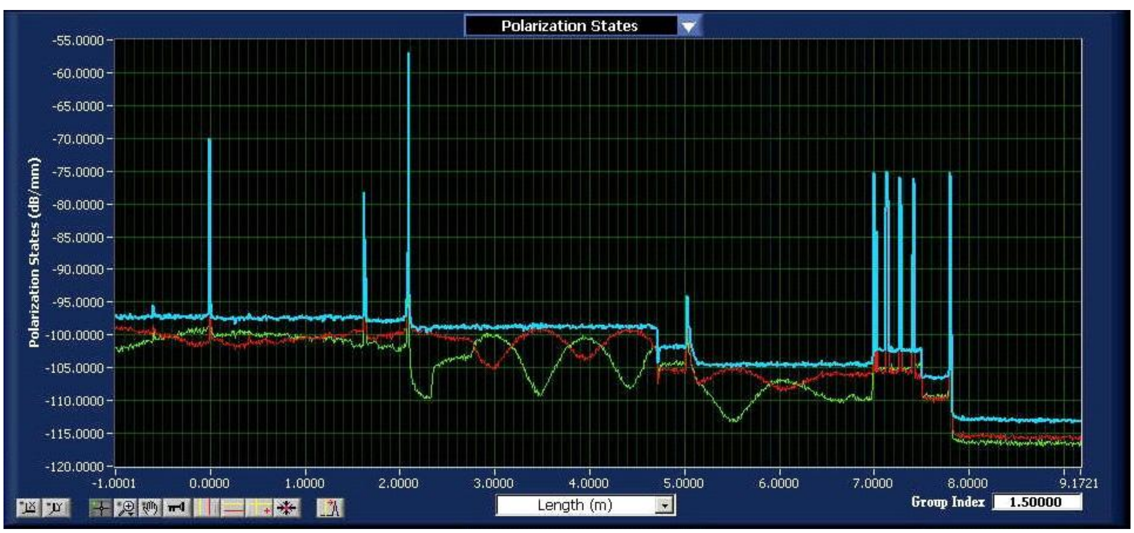

Figure 4.5. Sample Time Domain Data from the OBR. [11]

4.2.6 Frequency Domain

The data in the frequency-domain plot is calculated based on the cursor location and integration width of the time-domain data contained in the plot window above. Therefore it is possible to sectionalize a device or system and determine the amplitude and phase response of each interface or optical path separately, by zooming in and isolating them in the time-domain plot. This provides a powerful means for quickly and easily identifying faults and pinpointing their cause within a component, module, or subsystem.

The lower plot can display both the amplitude and phase derivative of the frequency domain data. The amplitude corresponds to the return loss of the device under test. By selecting a single reflection in the time-domain plot, it possible to measure the return loss from each interface individually within a device or subassembly. The Integrated Loss indicator yields a single average loss value for quick pass/fail evaluation for each optical path or interface.

The phase derivative plot in the frequency-domain yields the group delay of the device under test. Again, the group delay characteristics of individual optical paths within a device can be characterized by selecting the appropriate impulse in the time-domain plot.

Figure 4.6. Return loss in the frequency domain (bottom plot) based on highlighted section of data in the time domain (top plot). [11]

Chapter 5

Experimental studies using OBR

Chapter five demonstrates experimental studies that were performed on Luna instrument 4200 series OBR. The details are as follows.

5.1 Objective of the Experiment:

To find out the length of a short network fiber, finding bending loss, and to locate a splice on a fiber. This experiment had been done by me in in LAB of Optiphase, INC.

5.1.1 Equipment:

- OBR 4200
- Fiber Jumper 253.5m long, single mode fiber 3 m, and 23 m single mode fiber.
- Splice

5.1.2 Experimental Setup

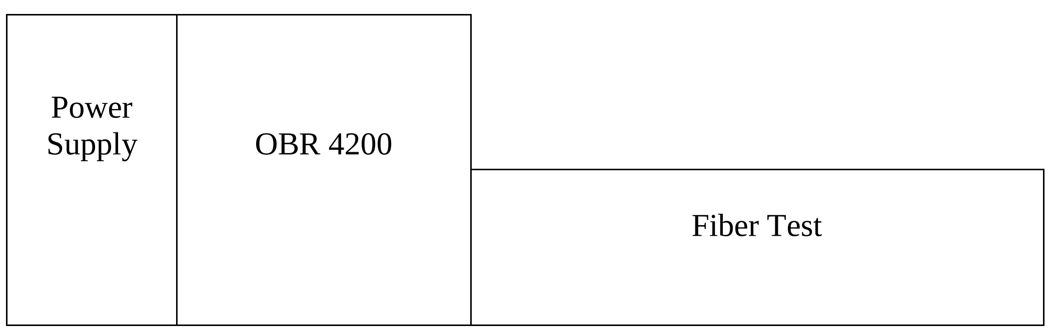

Figure 5.1 Experimental setup used to perform the experiment [3]

5.1.3 OBR Specification:

The OBR 4200 Luna instrument comes equipped with exhaustive user manual. Due to the fragility of the OBR equipment, it was that the instructions in the manual were accurately followed. The manual also held specification for the instrument.

Specifications are as follows.

PARAMETER SPECIFICATION UNITS

Maximum Device Length:

Device length	0 to 500 m

Spatial Resolution:

Event resolution	< 3 mm
Sampling resolution	0.3 mm

Center Wavelength:	1542 nm

Integrated Return Loss Characteristics:

Dynamic range	50 dB
Total range	-10 to -120 dB
Sensitivity	-120 dB
Resolution	±0.2 dB
Accuracy	±0.4 dB

Integrated Insertion Loss Characteristics:

Dynamic range	16 dB
Resolution	±0.1 dB
Accuracy	±0.2 dB

Measurement Timing

2.6 seconds overhead per scan plus	0.12 s/m

Optical Output

Connector type	FC/APC -
Output power	10 mW
Launch condition	Single-mode output standard. Multimode output available with Mode-Conditioner accessory.

Environmental

Operating temperature	0 to +40 C
Storage temperature	-20 to +60 C

Power

Battery life	5 hr
Battery charging time	5 hr

Dimensions and Weight

Size	8.5(L) x 10.7(W) x 3.85(H) in
Weight	9.8 Ibs

5.2 Observation:

5.2.1 Measuring Fiber Length Using OBR4200

In this case a 253.5m fiber jumper (Figure 5.2), this kind of Jumper is used for all kind of industry and it is a single mode fiber, the jumper has a splice around it. It is connected to the OBR4200 Luna as shown in (Figure5.3). In the setting menu the length starting from100m to 300m as shown in (Figure 5.4). We measure basically from the beginning of it to the back reflection of the end of this jumper. It tells us where the end of the fiber is, measuring time it takes for wave length 1.5 micro- meter to travel down the jumper hit the back reflection of 4% of the selected end and comeback.

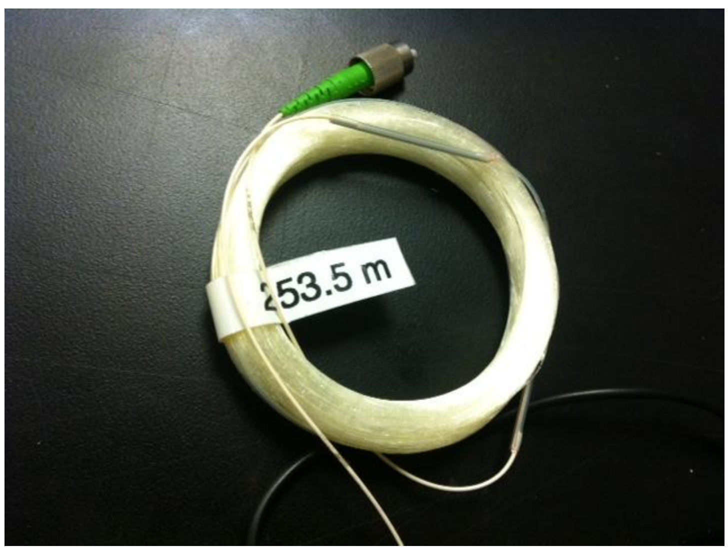

Figure 5.2 Fiber Jumper [12]

Figure 5.3 OBR 4200 Luna [12]

Figure 5.4 settings menu for the OBR [12]

When the scan on the OBR4200 is operating, the graph display shows the length of the fiber jumper (where the red line is X2=253.66m) is 253.66m long, this is a very accurate measurement (Figure 5.5).

Figure 5.5 OBR displays [12]

5.2.2 Fiber Bending Loss

In this case: A three meter fiber jumper (Figure 5.6) is connected to the OBR, this time a bending fiber was demonstrated(Figure 5.7) in order to find the bending loss location on the OBR graph display.

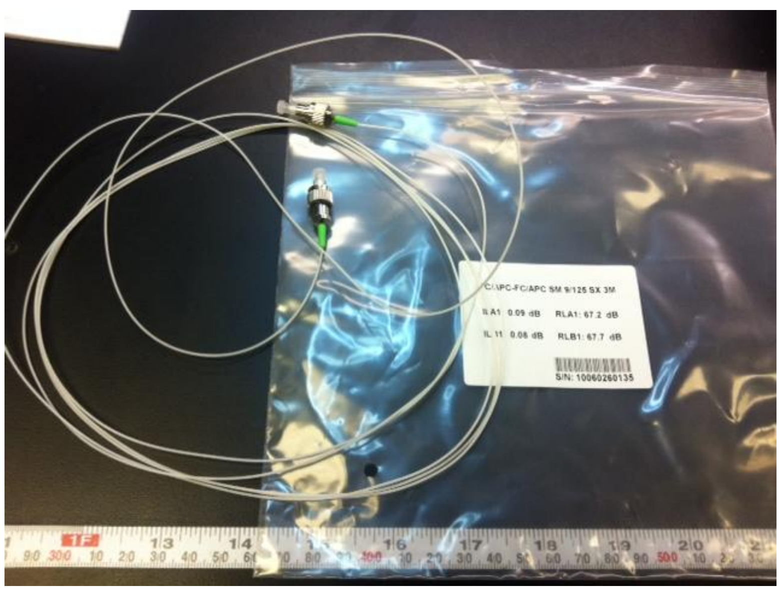

Figure 5.6 Fiber jumper [12]

Figure 5.7 Bending fiber [12]

Figure 5.8 Bending loss graph display [12]

OBR graph display shows the bending loss is at 3.0330 meter, the difference losses between X1 is (beginning of fiber-shown in yellow color) and X2 (end of fiber-shown in red color) is -72.630 – - 60.238 = - 6.176 dB as shown in (Figure 5.8).

5.2.3 Splice Fiber

In this case a sleeve splice (figure 5.9) is connected to a 23 meter jumper (Figure 5.10) and connected to the OBR (figure 5.11).

Figure 5.9 Sleeve splice [12]

Figure 5.10 - 23 meter jumper [12]

Figure 5.11 OBR connections [12]

The OBR display shows that the fiber length is 23.149 meters, at 2.246 mm the splice is taking place. In the graph dx = 15.08 mm is the distance from the connector x1 to the splice at x2 as shown in (figure 5.12).

Figure 5.12 OBR display for a splice [12]

This experiment shows that Optical Backscattering Reflectometer (OBR) is very accurate instrument, it is used for smaller measurements like medical devices. OBR can find the end of the fiber and bending losses. OBR can also detect multiple splices in the fiber. It can tell where every splice is, by measuring backscatter signal. It measures the round trip time it takes an optic signal to travel from one end of the fiber till the splice end and back.

OBR 4200 is the industry's only portable device. It cost $60,000. OBR does a very fine measurements and it has an amazing accuracy.

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