INVESTIGATION OF THE EFFECTS OF MACRO BENDING LOSS ON STEP INDEX SINGLE MODE FIBER

By

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Abstract

The objective of the thesis are to calculate power loss due to bending, to determine the spectral window at which fiber can effectively operates, to predict bend loss for a higher wavelength from the trend of shorter wavelengths and investigates the variation constants of optical fiber (MAC) factor,with respect to using Laser stage lighting, He-Ne laser and Diode laser, with wavelengths in the visible and infra red region of an optical spectrum.

In this thesis, a single mode fiber (SMF) was bent to various bend radius with a specially designed, adjustable fiber bending device and out put power was measured using a lock in amplifier. Thus, studying the relationship between macro bending and attenuation would enable us to maximize the performance of an optical fiber. As a whole in my experimental investigation was made of the bending losses in step index single mode fiber wave guide with different parameters of the equivalent step profile for bending radii from 0.5cm to 10.05cm with steps of 0.5cm, with the attenuation coefficient range is 0.045 dB/m to 0.475 dB/m,0.065 dB/m to 0.48 dB/m and 0.10 dB/m to 0.61 dB/m for the wavelengths 532nm, 633nm and 808nm respectively

As signal wavelength passes the cut off wavelength, attenuation decreases sharply due to disappearance of higher order mode. At wavelengths longer than cut off wavelength, attenuation increases with wavelength increases. Furthermore, attenuation is inversely proportional to bending radius measured at transmission wavelengths increases.

This study shows that attenuation introduced by macro bending depends on wavelength and bending radius. Based on these findings, one can minimize the adverse impact of macro bending. As a whole the results from the experiment have suggested that the optical power loss due to bending at the visible spectrum is more apparent than loss due to other effects such as absorption and scattering.

Acronyms

a.u	Arbitrary Unit
FTTH	Fiber-to-the-Home
IR ..	Infra red
ITU-T	International Telecommunication Union-Testing
LASER	Light Amplification Stimulated by Emission of Radiation
MDUs	Multiple-Dwelling Units
MFD	Mode Field Diameter
NA	Numerical Aperture
ppm	parts per million
SMF	Single Mode Fiber
SFUs	Single-Family Units
UV	Ultra Violet

Key words: macro bending ; optic beam launch; optical spectrum; radius of curvature: Single mode fiber: spectral window; power loss

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Chapter 1

Introduction

With our insatiable appetite for transmitting more information at a faster rate, our society is moving towards converged networks, carrying voice, data, and video on one medium, optical fiber. Optical fiber is a dielectric wave guide made of glass or plastic consisting of a core, cladding and a sheath or jacket. The index of refraction of the assembly varies across the radius of the cable, with the core having a constant or smoothly varying index of refraction and the cladding region having another constant index of refraction[1].

An optical fiber produced by conventional method, the signal losses of substantial level may be introduced either by turning the fiber about a point with relatively smaller radius of curvature or by waviness introduced during the sheathing of the fiber. It has been observed that a planar wave front, which must propagate through a bend, has different path lengths between the center of the core and its outer radius. A shift in mode field diameter of fiber on its bending has been observed to result in energy losses there by resulting in increase in bending loss of the fiber[2].

Optical fibers suffer from macro-bending loss at bends or curves on their paths. This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding and hence the guidance mechanism is inhibited, which causes light energy radiated from the fiber. So part of the mode in the cladding needs to travel faster than the velocity of light in that medium. The simulation of fiber bending loss began in 1970s by D. Marcuse which developed the basic model for predicting the bending loss of optical wave guide/fiber assuming a core-infinite cladding structure in a cylindrical coordinate system. And again Susanna Cattelan, Marco Ruzzier, Martino Travagnin also predict macro bending loss in bend insensitive fibers[3].

Macro bending occurs in a large deflection of the fiber axis, where large is defined relative to the fiber core diameter, such as that associated with spooling or the presence of loops and fibers are bent with a macroscopic radius of curvature, i.e in the range of centimetres. Macro bending is a deterministic problem in a bend at constant radius of curvature. Phenomenological, for small variations around a given profile design, there is a strong and linear correlation between the log of macro bending loss (at fixed radius of curvature R) and the so-called MAC factor, defined as[4]

$$MAC = \frac{MFD(\mu m)}{\lambda_c(\mu m)} \tag{1.0.1}$$

Where MFD is mode field diameter and λ_c is critical wavelength. Either the fiber or cable effective cut off can be used to calculate the MAC factor. Macro bending loss is proportional to the integral of mode power outside the radiation caustic. If one falls back to a ray-optic view (which is applicable only to multi mode fibers), one realizes that the critical angle for total internal reflection can be exceeded in a bent portion.

Strictly speaking, there is mechanical tension in the bent fiber so that the inside is compressed, the outside expanded. This creates deviations of the refractive index, effectively lowering it on the outside[5]. The mechanism just described is counteracted by this, but it is not compensated. It should be clear that the critical radius at which radiative loss begins must be proportional to the bend radius of the fiber. On the other hand, the modal field radially decays exponentially. These bends could cause the light in the core to hit the core cladding interface at an angle less than the critical angle and so that the light energy would not be internally reflected, but rather lost to the cladding material. However, the bending loss is primarily introduced during cabling and installation since practicality prevents fibers from being perfectly straight when installed. Thus, knowing the critical bend radius, the bend radius beyond which attenuation rapidly increases, the performance of optical networks can be optimized. By determining the relationship between the bend radius and the attenuation, guidelines for installation can be established to minimize signal loss. Furthermore, the macro bending loss caused by loss of power due to radiation at optical fiber. It will result in no significant radiation loss if it is of sufficiently large radius. There is a component of the poynting vector radially out ward; this implies energy radiated away from the guided mode.

In a wave-optic picture the field distribution of any mode is not restricted to the core, but extends into the cladding. As the fiber is being bent, there must be a certain distance from the fibers axis toward the outside of the curve where the propagation velocity (as determined by the effective index for that mode) begins to exceed the maximum possible velocity in the cladding. Of course, the velocity is not actually exceeded rather, the phase fronts cease to be plane and fall behind. For slight bends the excess loss is extremely small and essentially unobservable. If a bend radius is made a bit smaller once this threshold point has been reached, the losses suddenly become extremely large [7].

Attenuation is the loss of optical power or weakling of the optical signal travels along the fiber. It is a result of macro and micro bending, Rayleigh scattering, absorption, and other loss mechanisms[4]. Each loss mechanism contributes to the total amount of fiber attenuation. The most common source of attenuation in optical fibers occurs when light scatters in different directions by Rayleigh Scattering. It is the loss of the optical signal due to the molecular imperfections or the lack of optical purity in the fiber and from the basic structure of the fiber. Scattering is cumulative, meaning that the further the light travels through a medium, the more likely the light is going to scatter. This is denoted with Eq (1.0.2)

$$S_R = (1 - S)^D \tag{1.0.2}$$

where S_R is the remaining light, S is the fraction of light absorbed per unit length and D is the total length of the fiber.

Rayleigh scattering is also dependent on the size of the particles relative to the wavelength of the light[6]. Thus, as the wavelength approaches the particle size, scattering occurs more. For a transparent solid, the scattering loss in decibels per kilometre is given

$$S = \frac{A}{\lambda^4} \tag{1.0.3}$$

where S is the scattering, A is the constant depending on the material and λ is the wavelength of the light. Scattering can couple energy from guided to radiation modes, causing loss of energy from the fiber. There are unavoidable Rayleigh scattering losses from small scale index fluctuations

Rayleigh scattering, does not depend only up on the quality of the core material. The cladding material may also be significant. In the process of total internal reflection the electromagnetic fields penetrate the core-cladding interface and extend in to the cladding. Thus, a fraction of the total optical power propagates in the cladding. If the cladding material is of poor quality or is highly absorbing; it contributes to the overall fiber attenuation. Fibers required to have minimal attenuation are made with the inner regions of the cladding material high in quality and as carefully controlled as the core. It is then necessary to ensure that any light scattered in to the cladding does not propagate and enter the detector, because this is likely to increase the range of propagation velocities and make the fiber dispersion worse. Two steps can be taken to avoid this the outer layer of the cladding can be made absorbing so that the scattered rays are attenuated there but the propagating light is unaffected; the cladding itself can be surrounded by a protecting polymer layer of higher refractive index in to which the scattered rays pass and are absorbed.

Attenuation can also occur due to absorption. It is the process by which impurities in the fiber absorb optical energy and dissipate it as heat, causing a decrease in the optical signal.like Rayleigh Scattering, absorption is cumulative. Thus it depends on the amount of material the light has to pass through. This is denoted with the Eq (1.0.4)

$$S_R = (1 - \alpha)^D \tag{1.0.4}$$

where S_R is the remaining light, α is the fraction of light absorbed per unit length and D is the total length of the fiber. Attenuation owing to radiative effects originates from perturbations (both microscopic and macroscopic) of the fiber geometry.

The term launching loss refers to an optical fiber not being able to propagate all the incoming light rays from an optical source. This occurs during the process of coupling light into the fiber (e.g., losses at the interface stages). Rays launched outside the angle of acceptance excite only dissipative radiation modes in the fiber. In general, elaborate techniques have been developed to realize efficient coupling between the light source and the fiber, mainly achieved by means of condensers and focusing lenses. The focused input beam of light needs to be carefully matched by fiber parameters for good coupling.

Connector losses are associated with the coupling of the output of one fiber with the input of another fiber, or couplings with detectors or other components. The significant losses may arise in fiber connectors and splices of the cores of the joined fibers having unequal diameters or misaligned centres, or if their axes are tilted. Mismatching of fiber diameters causes losses that can be approximated by $10log(d/D)$. There are other connection losses such as offsets or tilts or air gaps between fibers, and poor surface finishes.

To take full advantage of fiber characteristics in transmission systems of very low intrinsic attenuation, the contribution of losses from other sources must also remain very small. The attenuation $a_s(d)$ due to coupling efficiency may be expressed as:

$$a_s(d) = -10log\eta(d) \tag{1.0.5}$$

where $\eta(d)$ is the coupling coefficient.

1.1 Motivation and Objectives

Hopefully, research into this area would allow for optimum performance of the fiber and ease of installation, spearheading the move to converged optical networks. Of course, it is very important that the macro bending with radius of curvature approximating to the fiber radius are not produced in the fiber cabling process. These macro bends can cause significant losses from cabled fibers. Of importance to this thesis study is power loss specifically macro bending. For telecom networks bend loss has hardly been an issue for many years. For most of the applications which use optical fibers such as in communications, the phenomena of bend loss is disadvantage because of its adverse effect on the power budget. However, it has also been exploited in a range of practical devices. It has been used as a transduction mechanism in fiber optic sensors such as water level sensors and displacement sensors. It has been used as a means to monitor the optical power level in fiber without breaking the transmission path. Macro bending loss is sometimes assumed intuitively that if a fiber is bent, then losses will be introduced into the transmission path. This is not true as the inside of a fiber is normally seen as a mirror to light rays, and slight bends in the fiber do not introduce losses. Qualitatively these curvature loss effects can be explained by examining the modal electric field distributions. Any bound core mode has an evanescent field tail in the cladding which decays exponentially as a function of distance from the core this field tail moves along with the field in the core part of the energy of a propagating mode travels in the cladding. When a fiber is bent, the field tail on the far side of the center of the curvature must move faster to keep up with the field in the core for the lowest order fiber mode. There have been very few investigations which employ this wavelength dependent characteristic for practical sensing applications. As the signal wavelength decreases below the critical wavelength (λ_{ce}), extra modes appears which can interfere with each other and with the primary mode to cause performance problems since the fibers characteristics become less predictable.

Thus, the macro bending attenuation can be determined using the physical characteristics of the bent optical fiber such as its cut off wavelength and mode field diameter. As the wavelength increases, the mode field diameter increases, and more of the mode field is spread into the cladding. Thus, at the bend, the outer part of the cladding field has to travel faster than the velocity of light in the medium. This velocity is unattainable and, consequently, this results in radiation loss.

Recent improvements in fiber purity have reduced attenuation losses[6]. The optical fibers for telecommunications are required to operate with the lowest attenuation loss at a wavelength of about 1550nm[1]. As the requirement for optical performance of optical fibers is stringent, the source of attenuation loss in optical fiber needs to be eliminated at a wavelength of about 1550nm. However, certain physical constraints in which the optical fibers can be used result in increase in attenuation loss of the fiber and an important one of these physical constraints is bending loss of the fiber, which is introduced during bending of the fiber while transporting and installation. Therefore, if bending loss of a fiber increases it results in increase in the attenuation loss of the fiber. Bend insensitive single-mode fibers are attractive for FTTH applications because they can lower the installation costs and improve system performance. For MDUs and in-home wiring applications, bend radii in the range of 5 mm are very common and bending losses must be kept to minimum. Mostly holes has to be drilled through walls for FTTH, high way roads will be dug and even sometimes buildings will be destructed for long haul in order to avoid bending the fiber optic cable making it fiber installations visually unappealing. Service providers like Verizon and fiber optic manufacturers like Corning and researchers are working closely together to develop fiber that can handle the smaller bend radii encountered in SFUs, MDUs, in-home wiring and long line wiring.

1.1.1 General objective

In view of this it was thought of interest to investigate the effect of macro bending loss in optical fiber.

1.1.2 Specific objectives

✓ to calculate MAC factor of optical fiber

✓ to calculate power loss due to macro bending

✓ to calculate steady state attenuation

✓ to predict bend loss of the fiber and the spectral window at which a fiber can operate effectively and also

✓ to predict the intrinsic loss of the fiber and the dominant nature of macrobending in short wavelengths, particularly in the visible region.

1.2 Structure of the thesis

The thesis is organized as follows. chapter 1 is an introduction of optical fiber, motivation, objectives and the whole structure of the thesis. Chapter 2 presents basic theoretical analyses of macro bending losses for single mode fiber. Chapter 3 is the experimental material and procedure to measure macro bending loss in step index single mode fiber for different wavelengths. Chapter 4 provides the result and discussion performed macro bending of the optical fiber. Chapter 5 summarizes the main conclusions and key results of this thesis and presents a brief overview of future research work.

Chapter 2

Macro Bending Loss of Single Mode Fiber

2.1 Macro Bending loss in Step-Index single mode fibers

The bend curvature creates an angle that is too sharp for the light to be reflected back into the core, and some of it escapes through the fiber cladding, causing attenuation. This optical power loss increases rapidly as the radius is decreased to an inch or less[7]. Fibers with a high numerical aperture and low core/cladding ratio are least susceptible to macro bend losses. The total loss of a bending fiber includes the pure bending loss and transition loss caused by mismatch between the quasi-mode of the bending fiber and the fundamental mode of the straight fiber[8].

Since the advent of optical wave guides the phenomenon of bend-induced losses have been recognized. Macro bending loss could be oscillatory due to the interference of light reflected at the cladding coating boundary and or at the outer coating surface with the propagation mode. Bend loss in optical fiber attract a lot of attention in fiber and cable manufacturing, as minimizing the bend loss improves telecommunication networks, while in the sensing area it attracts attention as a transduction mechanism to measure different parameters[9].

2.1.1 Pure bend loss

In straight region of the fiber before the bend, the transverse mode of power, P_o is confined to the core so that it propagates along the fiber axis. While in the bend region of radius r_b and angle Φ the confining path is circular and hence modal wave front will propagate with a velocity linearly dependent on the radial distance from the center of curvature of the bend[2]. A guided mode when propagating around a bend must maintain the same angular phase velocity at all points over the plane that is transverse to the propagation direction. That is at a certain radial position outside the bend known as critical radius r_c (radiation caustic) the mode tangential velocity is equal to the speed of the light in the medium. At radii beyond this, the velocity exceeds that of light and hence as shown in the Figure 2.1 the power in the shaded tail P_c propagates along a tangential path and thus radiates away. The resultant reduced guided power is given by[10]

$$P(r_b, \Phi) = P_o - P_c \tag{2.1.1}$$

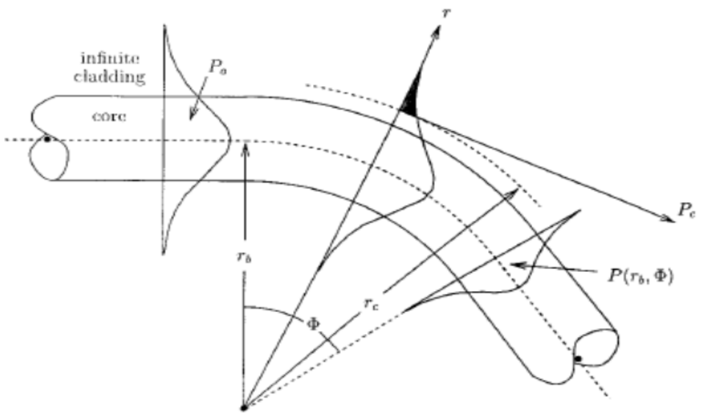

Figure 2.1: Pure bend loss mechanism

2.1.2 Transition loss

Transition loss arises due to the changes in the mode field characteristics when the fiber is bent. The mode profiles in the straight and the bent fiber segments are not identical and this leads to an incomplete transformation of a guided mode in the straight section into a superposition of guided modes in the bent section. As shown in Figure 2.2 in the bend the central maximum of the mode profile is shifted radially outward by a distance δ in comparison to fiber segment mode profile. At junction 1 between the straight and the bent fiber segments, a portion of the incident power excites the guided mode in the bent segment and the remaining power is coupled to the radiation modes in the cladding region. This power coupling process between the guided and the radiation modes also occurs at junction 2. The total transition loss resulting from the presence of the bend takes into account the losses that occur at both junctions. The mode shifting also has the effect of enhancing the pure bend loss by increasing the power in the shaded tail region [11].

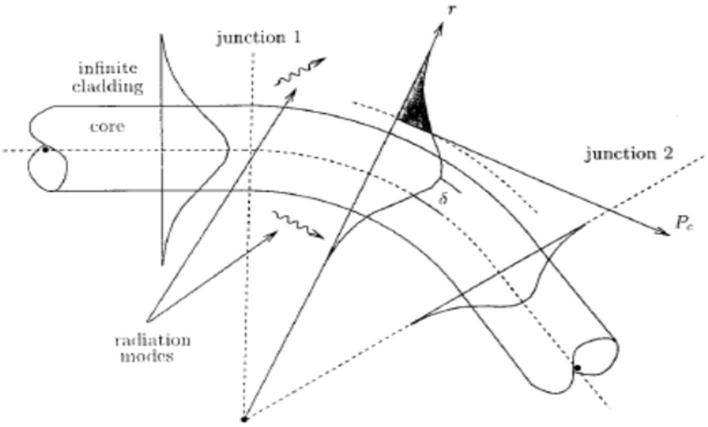

Figure 2.2: Transition bend loss mechanism

2.2 Transmission along fibers

Light that finds itself at one end of an optical fiber may or may not find its way to the other end. For a randomly chosen combination of the properties and configuration of the light, the optical power has only a small chance of propagating significant distances along the fiber. With proper design of the fiber and of the mechanism for launching the light, however, the signal carried by the light can be transmitted over many kilometres without severe leakage or loss. In its simplest form, an optical fiber consists of a long cylindrical core of glass, surrounded by a cladding of slightly less optically dense glass. Since both the core and cladding are transparent, propagation depends on the ability of the combination to confine the light and thwart its escape across the side of the fiber. It is the interface between the core and cladding that acts as a reflector to confine any light that would otherwise escape the core and leak away from the cladding into the outside world. The mechanism for confinement to the core is that of total internal reflection, a process that is easy to understand for a planar interface between two dissimilar dielectric media. That process applies as well to the cylindrical geometry of the interface between the core and cladding of the optical fiber. When light strikes the planar interface between two dissimilar transparent media, part of the light is transmitted and the rest is reflected. The proportions of each depend on the impedance mismatch between the two media; this, in turn, depends on the dissimilarity of the indices of refraction of the two materials[12].

When light strikes the interface at an angle to the normal, rather than head-on, the light that is transmitted is refracted, or bent away from its original direction, in accordance with Snell's law,

$$n_1 sin\theta_1 = n_2 sin\theta_2 \tag{2.2.1}$$

where n_1 and n_2 are the refractive indices of the two media and θ_1 and θ_2 are the angles of the ray to the normal to the interface in the two regions. If the light is incident onto the interface from the denser medium and if the ray direction is close to grazing, so that the

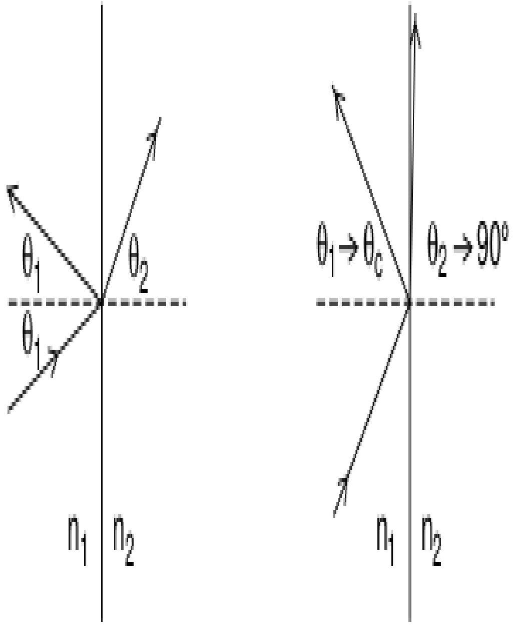

Figure 2.3: Snell's law determines the angle of refraction θ_2 at an interface; the angle of reflection θ_1 equals the angle of incidence

angle of incidence θ_1 is sufficiently large, then it may happen that $n_1 sin\theta_1$ exceeds n_2 and there is then no solution for the angle of refraction θ_2 from Snell's law, since the quantity $sin\theta_2$ can never exceed unity. Instead of partial reflection into the denser medium and partial refraction into the other region, there is then no transmission into the less dense medium. Rather, all of the light is reflected back into the denser medium. Total internal reflection occurs (internal to the denser medium in which the light originated), and the escape of the light into the less dense medium has been thwarted.

There is more to the process of total internal reflection at a planar boundary than merely reflection from the interface. Although the light does not leak into the less dense medium and thereby get transmitted outward, it does seep across the interface and propagate, but only parallel to that interface surface. In the direction normal to the interface, there is no propagation on the less dense side of the surface but the strength of the light that appears there decays exponentially. The spatial rate of decay increases with the angle of incidence, beyond the critical angle at which total internal reflection begins. If the decay is sufficiently strong, the light that seeps across is effectively constrained to a thin layer beyond the interface and propagates along it, while the light left behind is reflected back into the denser region with its original strength. The reflection coefficient is 100%. There is undiminished optical power flow along the reflected ray in the denser medium, but only storage of optical energy in the light that seeps across the interface into the less dense region.

The same process occurs along the curved, cylindrical interface between the core and cladding of the optical fiber. When the light strikes this interface at a sufficiently high grazing angle, total internal reflection occurs, keeping the optical power propagating at an angle within the core and along the axial direction in the cladding. The reflected light strikes the core again on the other side of the axis and is again totally internally reflected there. This confines the light to the core and to a thin layer beyond the interface in the cladding and keeps it propagating indefinitely along the axial direction. The overall result is that the light is guided by the fiber and not permitted to leak away across the side of the fiber, provided the light rays within the core encounter the interface at a sufficiently high grazing angle[13].

Because of refraction at the fiber air interface, the ray bends toward the normal. The refracted ray hits the core-cladding interface and is refracted again. However, refraction is possible only for an angle of incidence ϕ such that $sin\phi < n_2/n_1$. Since such reflections occur throughout the fiber length, all rays with $\phi > \phi_c$ remain confined to the fiber core. This is the basic mechanism behind light confinement in optical fibers.

Attenuation is measured in decibels (dB) and is a measurement of relative intensity such that

attenuation $(dB) = -10log(I/I_0)$

Where I is the measured output power and I_0 is the reference input power.

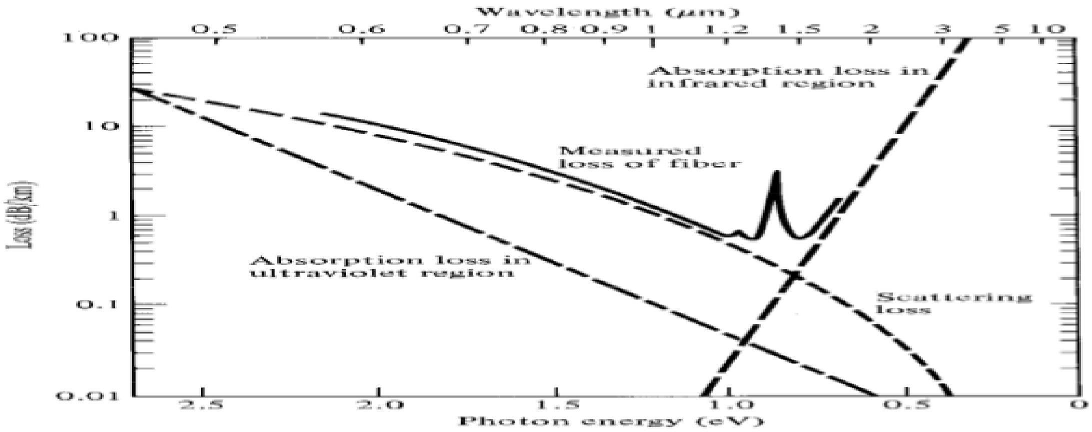

Figure 2.4: Light confinement through total internal reflection in step-index fibers

At a bend, the lights propagation conditions change and thus the optical signal is lost into the cladding. Under quite general conditions, changes in the average optical power P of a bit stream propagating inside an optical fiber are governed by Beers law:[12,14]

$$\frac{dP}{dz} = -\alpha P \tag{2.2.2}$$

Where α is the attenuation coefficient. If P_{in} is the power launched at the input end of a fiber of length L, the output power P_{out} from Eq. (2.2.2) is given by

$$P_{out} = P_{in} exp(-\alpha L) \tag{2.2.3}$$

It is customary to express α in units of dB/km by using the relation given below it is refered to it the fiber loss parameter.

$$\alpha(dB/km) = -\frac{10}{L}\log_{10}(\frac{P_{out}}{P_{in}}) \approx 4.343\alpha \tag{2.2.4}$$

At a sharp bend, the outer part of the mode field must travel faster than the inner part to maintain this wave front. Consequently, the outer part must travel faster than

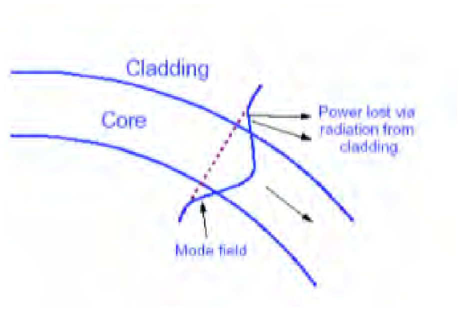

Figure 2.5: At a sharp bend, the outer part of the mode field must travel faster than the velocity of light in the medium and energy is lost through radiation

the velocity of light in the medium and since this is not possible the energy of this outer part dissipates into the cladding (See Figure 2.6).

Generally, the transmission of light along an optical fiber, can be described by two theories. According to the first theory, light is described as a simple ray. This theory is the ray theory, or geometrical optics, approach. The advantage of the ray approach is that you get a clearer picture of the propagation of light along a fiber. The ray theory is used to approximate the light acceptance and guiding properties of optical fibers. According to the second theory, light is described as an electromagnetic wave. This theory is the mode theory, or wave representation, approach. The mode theory describes the behaviour of light within an optical fiber. Two types of rays can propagate along an optical fiber meridional rays and skew rays[15].

Meridional rays are rays that pass through the axis of the optical fiber. They are used to illustrate the basic transmission properties of optical fibers. They can be classified as bound or unbound rays. Bound rays remain in the core and propagate along the axis of the fiber. Bound rays propagate through the fiber by total internal reflection. Unbound rays are refracted out of the fiber core fig 2.6 shows a possible path taken by bound and unbound rays in a step-index fiber. Fig 2.6 assumes the core-cladding interface is perfect. However, imperfections at the core-cladding interface will cause part of the bound rays to be refracted out of the core into the cladding. The light rays refracted into the cladding will eventually escape from the fiber. In general, meridional rays follow the laws of reflection and refraction. Skew rays are rays that travel through an optical fiber without passing through its axis.

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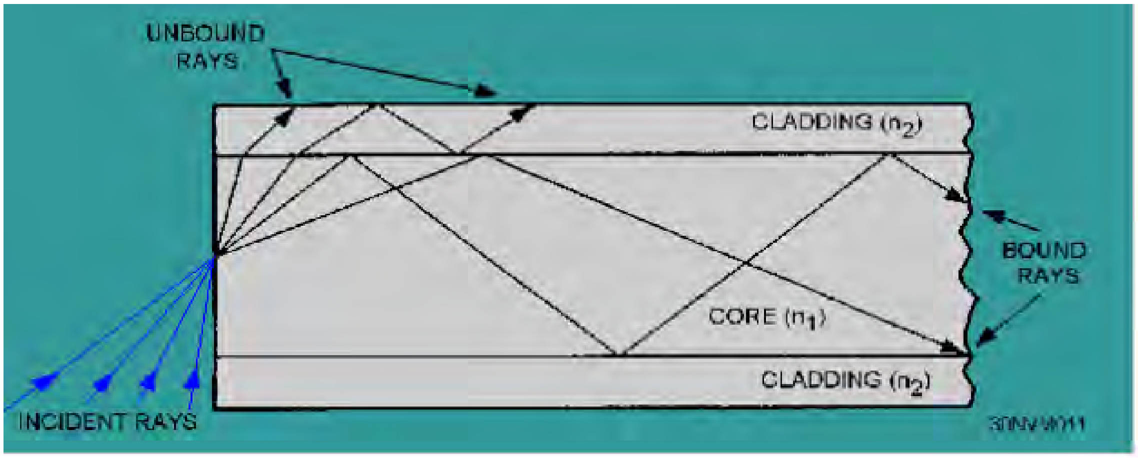

Figure 2.6: Bound and unbound rays in a step-index fiber

Rays that enter the fiber must intersect the core-cladding interface at an angle greater than the critical angle θ_c. Only those rays that enter the fiber and strike the interface at these angles will propagate along the fiber. when a light ray is launched into a fiber is shown in Figure 2.7 the incident ray I_1 enters the fiber at the angle θ_a. I_1 is refracted upon entering the fiber and is transmitted to the core-cladding interface and the ray then strikes the core-cladding interface at the critical angle θ_c. I_1 is totally reflected back into the core and continues to propagate along the fiber. So the incident ray I_2 enters the fiber at an angle greater than θ_a and again, I_2 is refracted upon entering the fiber and is transmitted to the core-cladding interface,it strikes the core-cladding interface at an angle less than the critical angle θ_c and refracted into the cladding and is eventually lost.

Wave fronts are required to remain in phase for light to be transmitted along the fiber. Consider the wave front incident on the core of an optical fiber as shown in figure 2.8. Only those wave fronts incident on the fiber at angles less than or equal to the critical angle may propagate along the fiber. The wave front undergoes a gradual phase change as it travels down the fiber. Phase changes also occur when the wave front is reflected. The

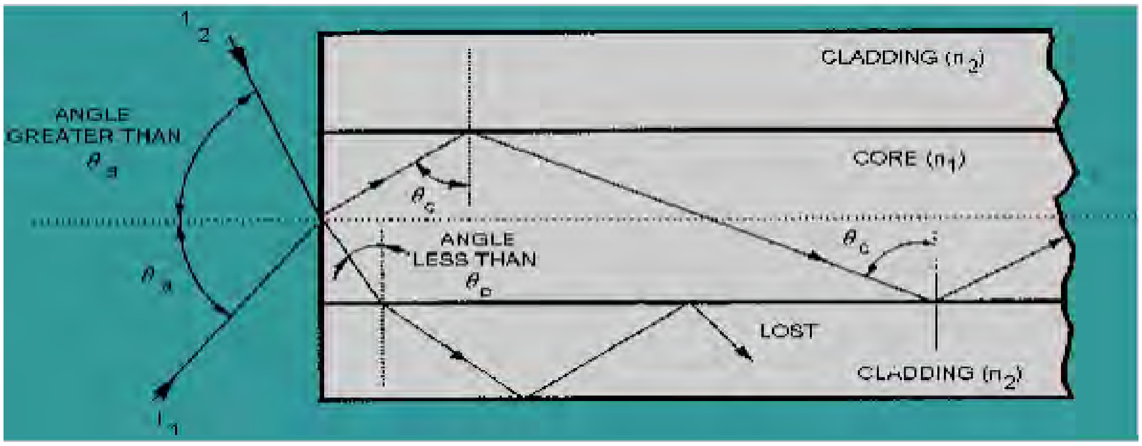

Figure 2.7: How a light ray enters an optical fiber

wave front must remain in phase after the wave front transverses the fiber twice and is reflected twice. The plane waves repeat as they travel along the fiber axis. The direction the plane waves travel is assumed to be the z direction as shown in figure 2.8. For a given mode, a change in wavelength can prevent the mode from propagating along the fiber. The mode is no longer bound to the fiber it is said to be cut off. Modes that are bound at one wavelength may not exist at longer wavelengths. The wavelength at which a mode ceases to be bound is called the cutoff wavelength for that mode. However, an optical fiber is always able to propagate at least one mode. This mode is referred to as the fundamental mode of the fiber. The fundamental mode can never be cut off [16].

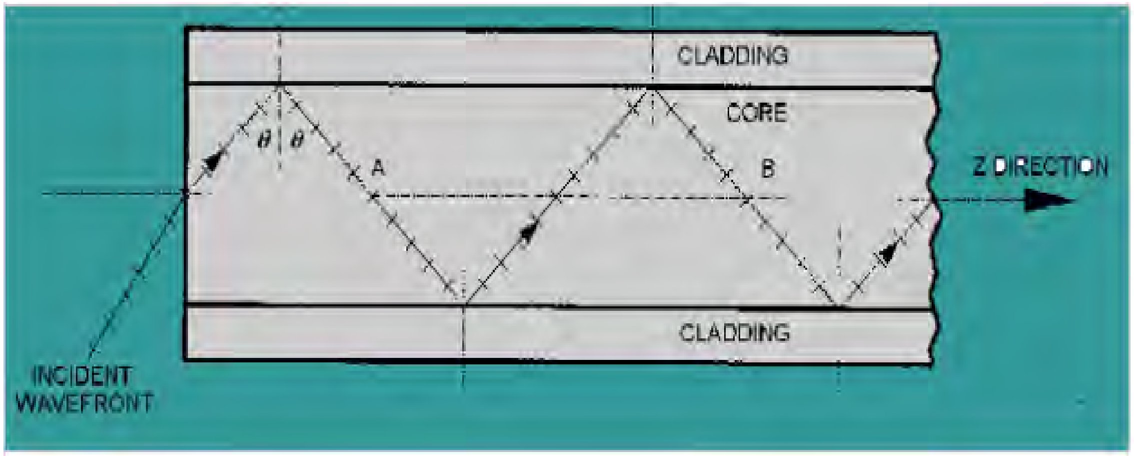

Figure 2.8: Wave front propagation along an optical fiber

2.3 Modes of Propagation in single mode fiber

For the cylindrical geometry of core and cladding in a fiber, the equivalent of a ray of light in an unbounded medium is any one of a set of modes of optical propagation. These refer to configurations of electromagnetic fields that satisfy Maxwell's equations and the boundary conditions imposed by the core−cladding interface and also conform to the total internal reflection requirement of grazing incidence to allow guided-wave propagation of the mode along the fiber.

These modes are nearly all hybrid, meaning that neither the electric nor the magnetic field of the mode is fully transverse to the axial direction of propagation, as can be the case for wave guides formed by hollow conducting pipes. Whereas the field configuration in a rectangular metallic wave guide varies as a sine function across the guide, that of an optical fiber follows a Bessel function variation. Bessel functions oscillate, much like trigonometric ones, but not with a constant amplitude. In the cladding,the fields decay in the radial direction away from the interface, but not exponentially as at a planar interface under total internal reflection. Rather, the fields in the cladding decay as modified Bessel functions, but the effect is the same: confinement to a thin layer just beyond the interface. At any frequency ω, optical fibers can support a finite number of guided modes whose spatial distribution $E(r, \omega)$ is a solution of the wave equation and satisfies all appropriate boundary conditions. In addition, the fiber can support a continuum of unguided radiation modes. Although the inclusion of radiation modes is crucial in problems involving transfer of power between bounded and radiation modes, they do play an important role in the bending of optical fiber. In any ordinary single mode fiber there are actually two independent, degenerate propagation modes. These modes are very similar, but their polarization planes are orthogonal. These may be chosen arbitrarily as the horizontal (H) and the vertical (v) polarization. Either one of these two polarization modes constitutes the fundamental HE_{11} mode. In general the electric field of the light propagating along the fiber is a linear superposition of these two polarization modes and depends in the polarization of the light at the launching point into the fiber.

Just as the modes of hollow metal pipes are classified as transverse electric (TE) and transverse magnetic (TM), the hybrid modes of optical fibers also come in two distinguishable varieties, labelled HE and EH, with pairs of subscripts appended to indicate the number of oscillations of the fields azimuthally (around the axis) and radially (across the core). For practical designs of optical fibers, dictated by the smallness of optical wavelengths, the indices of refraction of the core and cladding are very close to each other, and there exist combinations of the hybrid modes that are very nearly of the more familiar transverse, linearly polarized types and of greatly simplified description; these are designated LP modes. The dominant mode, which has no constraint of a minimum frequency, is the HE_{11} mode, also designated the LP_{01} mode in the simplified version. All other modes have a cut off frequency, a minimum frequency for axial propagation of a confined mode. Even the dominant mode, in practical cases, has fields that are virtually unconfined when the frequency is too low.

2.3.1 Mode coupling

One more consideration affecting propagation along an optical fiber is the possibility of mode coupling. Although the theoretical modes of propagation travel independently along fibers of perfect constitution and perfect geometry, real fibers inevitably have imperfections that can cause different modes to couple and exchange energy between them as they propagate. A fiber may be imperfect in geometry in that it may not be perfectly straight axially, or its core may not be perfectly round, or it may have been bent. The core and cladding may deviate from their nominal refractive indices. More importantly, there may be fluctuations in their material properties, or the graded-index profile may not be the ideal one. All such imperfections give rise to coupling between modes of propagation of the ideal version of the fiber, such that some of the power in one mode is drained and feeds another mode.

When the other mode becomes the stronger one, energy is fed back to the first mode and thereafter sloshes back and forth repeatedly between the modes as the light travels along the fiber. How many modes participate in this periodic exchange of energy depends on the nature of the fluctuations of the imperfections. A perturbation analysis of the effects of fluctuations in some parameter that would be constant in an ideal fiber reveals that the relevant property is the spatial Fourier spectrum of the fluctuations. The strength of the coupling between any two modes is proportional to the statistical average of the power spectrum of the fluctuations, evaluated at the difference between the propagation constants of the two modes in the ideal structure[17].

This implies that deviations on a large scale, such as gradual bending of the fiber, will affect only a certain group of modes. In this case, the spatial power spectrum exhibits a relatively narrow bandwidth,near zero spatial frequency. This allows only modes whose ideal propagation constants are very close to each other to be coupled by the large-scale fluctuations. Such deviations, therefore, couple only modes that are nearly degenerate (have nearly equal propagation constants). On the other hand, periodic fluctuations, such as striations in the material properties, exhibit a spatial spectrum that is peaked in a spectral region corresponding to the period of the striations. In that case,coupling will be significant for modes whose propagation constants differ by the spatial wave number associated with the periodicity of the fluctuations. One effect of coupling among modes is to increase losses along the fiber, because energy can get transferred to modes that are not trapped within the core. Some of that energy can then leak out into the cladding and be lost before it can return to the propagating mode. Another effect, however, is to average the dispersion associated with many modes and thereby reduce the overall pulse spreading. For example, for closely coupled modes, propagation delays may vary as only the square root of the distance travelled, rather than with the more severe variation, proportional to distance, for uncoupled modes.

2.3.2 Whispering-gallery mode

Whispering-gallery mode resonances correspond to light that is trapped in circular orbits just within the surface of the structure. The modes are most strongly coupled along the equatorial plane and they can be thought to propagate along a zigzag paths around the sphere. In the view of ray optics,the light is trapped inside the dielectric sphere by continuous total internal reflections at the curved boundary of surface. Whispering gallery modes occur at discrete frequency that depends on index of refraction n_s and radius of r_o of the sphere[18].

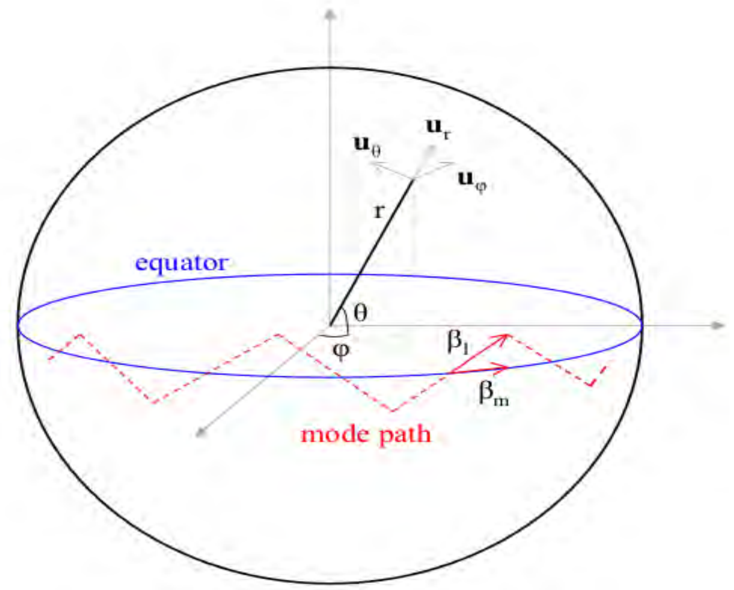

Figure 2.9: Whispering gallery modes

Each mode has a propagation constant β_1 parallel to the surface and in the direction of the zigzag path. The propagation constant has a value.

$$\beta_1 = \sqrt{\frac{l(l+1)}{R_o}} \tag{2.3.1}$$

The projection of the propagation constant is β_m it has a value

$$\beta_m = \frac{m}{R_o} \tag{2.3.2}$$

Whispering gallery modes are characterized by two polarization(transversal electric i.e.TE modes and transverse magnetic i.e. TM modes) and three mode numbers n, l, and m which are radial, angular and azimuthal mode numbers respectively. The value of l is close to the number of wavelengths that fit into the optical length of the equator. The value $l - m + 1$ is equal to the number of field maxima in the polar direction, i.e. perpendicular to the equatorial plane. Mode number n is equal to the number of field maxima in the direction along the radius of the sphere and $2l$ is the number of maxima in the azimuthal variation of the resonant field around the equator. The resonant wavelength is determined by the values of n and l.

Identification of whispering gallery modes, where radial mode number n equals to the number of field maxima in radial direction, l is the angular mode number and azimuthal mode number m equals to the number of field maxima in the equator plane. The fundamental mode is defined as $n = 1$ and $m = l$. The physical meaning of mode numbers is also seen.

2.4 Fiber Bandwidth

The concept of fiber bandwidth originates from the general theory of time invariant linear systems. If the optical fiber can be treated as a linear system, its input and output powers should be related by a general relation[12].

$$P_{out}(t) = \int_{-\infty}^{\infty} h(t - t^{'}) P_{in}(t^{'}) dt^{'} \tag{2.4.1}$$

For an impulse $P_{in}(t) = \delta(t)$,where $\delta(t)$ is the delta function, and $P_{out}(t) = h(t)$. For this reason $h(t)$ is called the impulse response of the linear system. Its Fourier transforms,

$$H(f) = \int_{-\infty}^{\infty} h(t) exp(2\pi i f t) dt \tag{2.4.2}$$

Provides the frequency response and is called the transfer function. In general, $|H(f)|$ falls off with increasing f, indicating that the high-frequency components of the input signal are attenuated by the fiber. In effect, the optical fiber acts as a band pass filter. The fiber bandwidth f_3 dB corresponds to the frequency $f = f_3$ dB at which $|H(f)|$ is reduced by a factor of 2 or by 3 dB. Note that f_3 dB is the optical bandwidth of the fiber as the optical power drops by 3 dB at this frequency compared with the zero-frequency response. In the field of electrical communications, the bandwidth of a linear system is defined as the frequency at which electrical power drops by 3 dB. Optical fibers cannot generally be treated as linear with respect to power, and Eq. (2.4.1) does not hold for them . However, this equation is approximately valid when the source spectral width is much larger than the signal spectral width ($V_\omega >> 1$). In that case, we can consider propagation of different spectral components independently and add the power carried by them linearly to obtain the output power.

2.5 Wave guide imperfection

An ideal single-mode fiber with a perfect cylindrical geometry guides the optical mode without energy leakage into the cladding layer. In practice, imperfections at the core-cladding interface (e.g., random core-radius variations) can lead to additional losses which contribute to the net fiber loss. The physical process behind such losses is Mie scattering, occurring because of index inhomogeneities on a scale longer than the optical wavelength. Care is generally taken to ensure that the core radius does not vary significantly along the fiber length during manufacture. Such variations can be kept below 1%, and the resulting scattering loss is typically below 0.03 dB/km. Bends in the fiber constitute another source of scattering loss. The reason can be understood by using the ray picture. Normally, a guided ray hits the core cladding interface at an angle greater than the critical angle to experience total internal reflection. However, the angle decreases near a bend and may become smaller than the critical angle for tight bends. The ray would then escape out of the fiber. In the mode description, a part of the mode energy is scattered into the cladding layer[12].

2.6 Cut off wavelength

Cut off wavelength of the LP_{11} mode forms one the most important characteristics of a single mode fiber. For numerous reasons concerning transmission performance (bandwidth, multipath interference, modal noise, etc.), it is desirable to operate fibers in the regime where only the fundamental mode propagates. It has already been noted that the well known weakly guiding analysis shows that a matched cladding optical fiber supports the propagation of only the fundamental LP_{11} mode when the normalized frequency (V) of the wave guide is less than 2.405. Therefore, the theoretical cut off wavelength for a step-index fiber, λ_c , is defined as

$$\lambda_c = \frac{2\pi n_1 a}{2.405}\sqrt{2}.\Delta \tag{2.6.1}$$

where n_1 is the refractive index of the core, a is the core radius, and Δ is the relative index difference between the core and cladding. At wavelengths greater than λ_c , the transverse propagation constant β_{t2} of the first higher order LP_{11} mode in the cladding region becomes a real number. This changes the solution for the electric field in the cladding from a decaying, evanescent field to an oscillatory, propagating field, thus resulting in radial energy flow (i.e., one that carries energy away from the fiber axis). The bound mode becomes a leaky mode.

2.6.1 Effective Cut off Wavelengths

Effective cut off wavelength is defined as that wavelength at which the ratio of the total power to the fundamental mode power is 0.1dB. Far below λ_c the LP_{11} mode is tightly confined within the core region and losses will generally be comparable to those of the fundamental mode. As the wavelength increases, the LP_{11} mode becomes less tightly confined to the core. The decreasing mode confinement gives rise to excess LP_{11} mode loss when axial imperfections, such as micro bends or macro bends, are present. Generally as one approaches, wavelengths 100 nm or so below λ_c , the LP_{11} mode becomes very loosely confined to the core and very lossy if the fiber axis is not maintained perfectly straight. Effective cut off wavelength is slightly smaller than the theoretical value of the cut off wavelength[12].

Chapter 3

Experimental Details

The equipments used in the entire experiment of this thesis are the following: single mode fiber, with length 2m and core radius(a) 4.15 μm, light sources such as laser stage lighting with operating power of 15mW and operating wavelength 532nm, He-Ne laser with operating power 0f 3mW and operating wavelength 633nm and Diode laser with operating power of 10mW and operating wavelength 808nm, stands, microscope objective and lens, chopper controller, lock-in amplifier, and slide micrometer gauge.

3.1 Experimental set up and measurement procedures

Using operating optical fiber source such as, laser stage lighting, He-Ne laser, and diode laser is providing a monochromatic red, green, and red light of wavelengths 532nm, 633nm and 808nm. The beam laser light passes through with 2m length fiber then using a 0.7mm light source aperture the spot size of the laser is then reduced to lesser diameter. To avoid losses through divergence of spot, light is collimated through a microscopic objective 18mm and 48mm focal length convex lenses it passed through another 0.7mm light source aperture to perfectly lessen its spot. As the launched beam passes through a 50% beam splitter, which splits into two paths. The light path collinear to the original laser source is directly recorded to the first photometer as I_i, later regarded as the input power, whereas, the other partial light path passes through the fiber and recorded as I_o. Finally connecting the one end of optical fiber to the reference light source and the other end to the lock in amplifier and then turn on the reference light source, chopper controller and lock in amplifier, laser beam was sent to the fibre the source of the laser and a detector where we used for light source and detection of light were employed. By repeat the above steps with bending radius (0.5cm upto 10.5cm with steps of 0.5cm) measured the output optical power. Moreover, the bend radius were measured using slide micrometer gauge to ensure both precision and accuracy in the results.

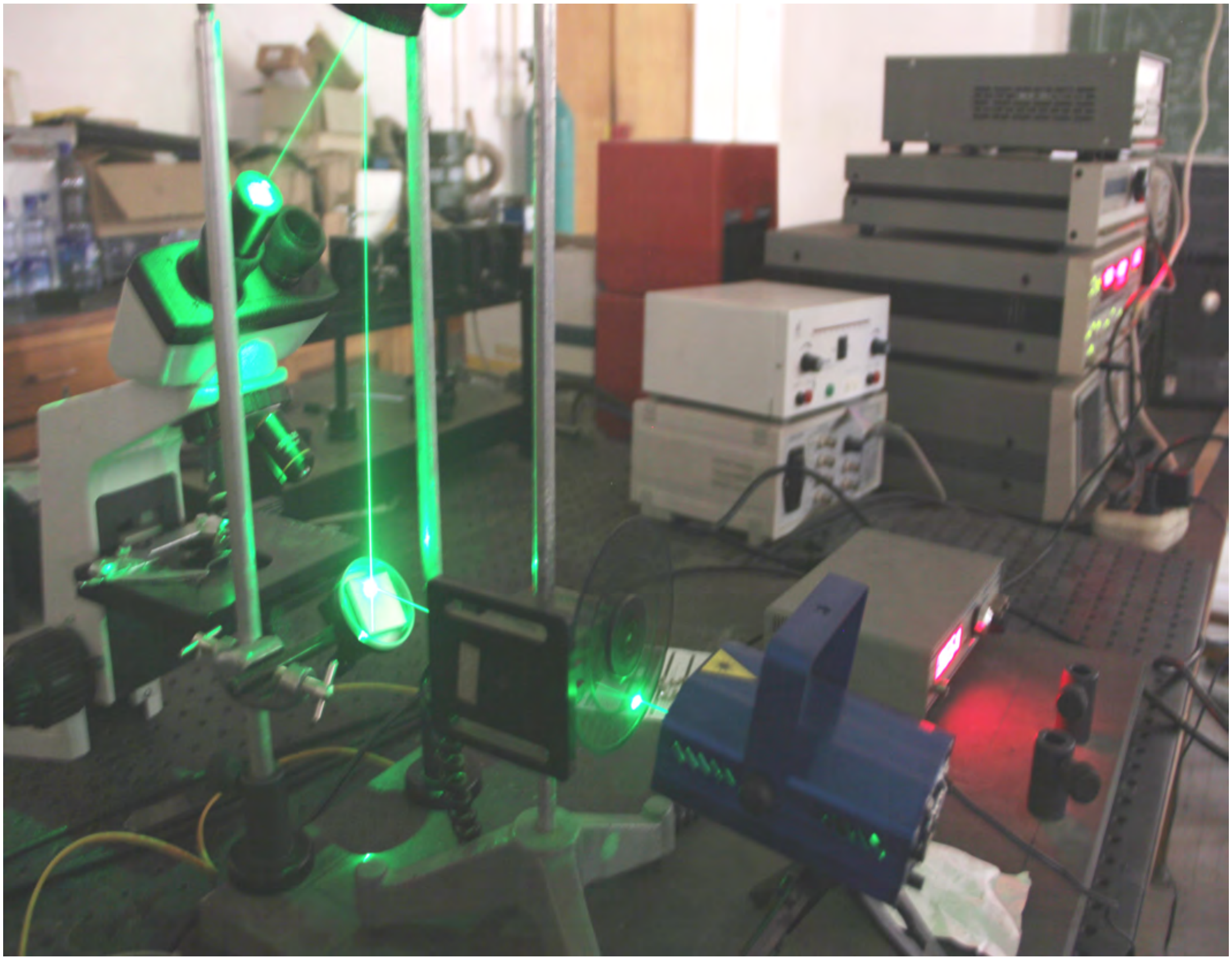

Figure 3.1: Experimental setup

3.2 Theoretical calculation of bending loss

For a single mode fiber of length L, the bend loss can be calculated using the equation [3.3.1] [18,19]

$$L_s = 10log_{10}(exp(2\alpha L)) = 8.686\alpha L \tag{3.2.1}$$

Where α is an bending loss coefficient which is determined by the fiber structure, bending radius and input wavelength of light. Often when bending reaches a critical radius of curvature (R_c), then loss due to bending can be neglected, and R_c is defined as[3.3.2] [20]

$$R_c = \frac{3n_2.\lambda}{4\pi(N.A)^3} \tag{3.2.2}$$

where R_c is the critical radius of bending, n_2 is the refractive index of the cladding ,$N.A$ is the numerical aperture of the fibre and λ is the wavelength.

The empirical formula defining macro bending attenuation required the attenuation to be in dB. This can be achieved by using[16,21]

$$Attenuationperunitlength(dB/m) = \frac{A}{\pi\frac{D}{2}} \tag{3.2.3}$$

where A is the attenuation (dB) caused by a half-loop bend with a diameter D (m).

Chapter 4

Result and Discussion

When there is no macro bending in the fiber, the attenuation of the fiber is associated with Rayleigh scattering[4,6]. Theoretically, Rayleigh Scattering and attenuation associated with inversely proportional to the fourth power of the wavelength.

As light is launched into the fiber it undergoes a decrease in the output intensity and these decrease output intensities with increases of the wavelength. That means, as the radius, R approaches to the radius of curvature, R_c and when R_c becomes equal to R, then it attains minimum bend loss and the loss will be negligible beyond R_c. In other words, the evanescent wave will be confined to the core region. That is, the loss is not due to bending rather it is due to the intrinsic nature of the fiber.

From Figure 4.1 when the bending radius increase, the attenuation is decreases exponentially until it reaches at a certain critical radius[for details see apendix A]. For any radius a bit smaller than this point, the losses suddenly becomes extremely large and from the graph there is a point where attenuation becomes steady. This is the case where the only dominating loss is scattering, absorption and other loss mechanisms excluding macro bending state. Even if the fiber is straight, there is a loss but this loss is not due to macro bending rather it is the minimum expected loss in the manufacturing stage (or the intrinsic nature of the fiber). Higher order modes radiate away faster than lower order modes.

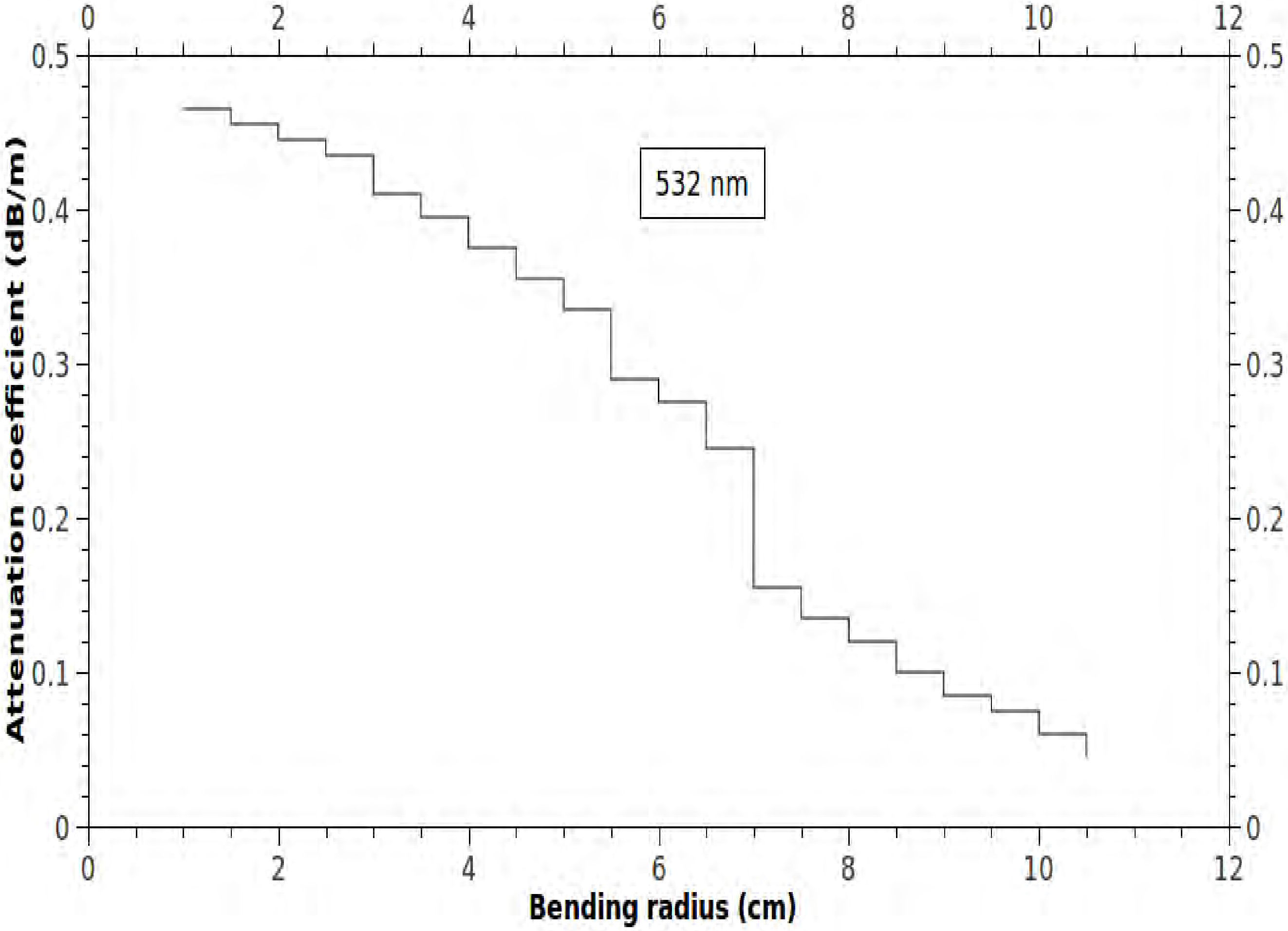

Figure 4.1: Attenuation coefficient Vs bending radius, at wavelength of 532nm

Figure 4.2 above and Figure 4.3 below shows the results of bending of optical fiber that, as the wavelength approaches 633nm and 808nm, the attenuation of the fiber increases.

As we saw from each graphs attenuation coefficient is proportional to the wavelength of the optical signal. As the wavelength increases, the mode field diameter increases, and more of the mode field is spread into the cladding. Thus, at the bend, the outer part of the cladding field has to travel faster than the velocity of light in the medium. This velocity is unattainable and, consequently, this results in radiation loss.

2.png

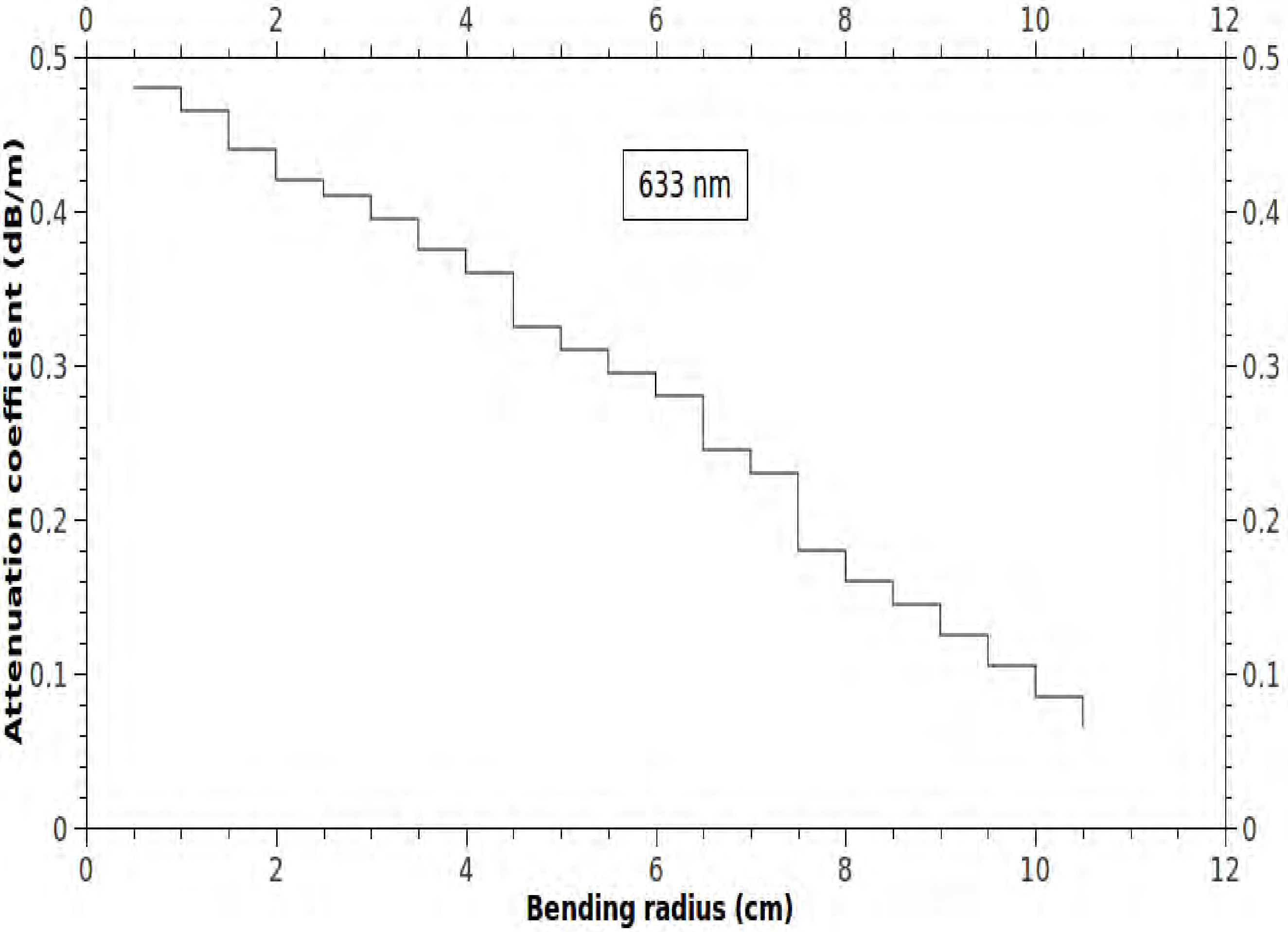

Figure 4.2: Attenuation coefficient Vs bending radius, at wavelength of 633 nm

In optical networks, attenuation degrades the performance of the transmission. A bend radius that results in high signal loss is the critical bend radius. Any bend radius smaller than the critical bend radius introduces enough attenuation to deem the fiber ineffective for communication. Therefore, for a single mode fiber any macro bends shorter than 6cm, attenuation increases rapidly.

Generally, from Figure 4.1, Figure 4.2 and Figure 4.3, there are a noticeable amounts of attenuation between the wavelengths of 532nm,633nm and 808nm. This increase in loss is caused by the appearance of a higher order mode in the fiber. This extra mode

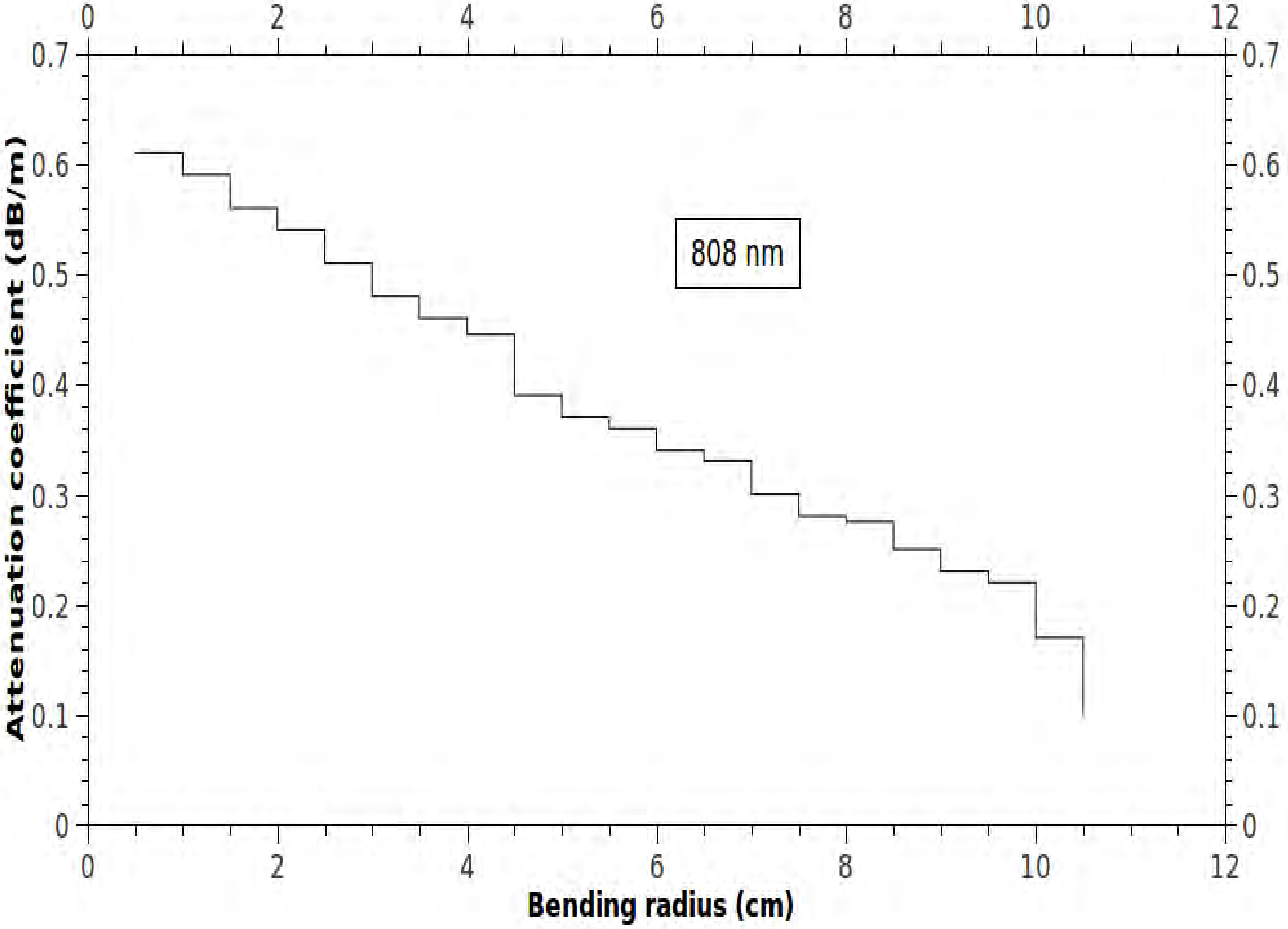

Figure 4.3: Attenuation coefficient Vs bending radius, at wavelength of 808 nm

occurs since the wavelength of the signal is shorter than the cut off wavelength(λ_{ce}) for a SMF optical fiber,and thus the fiber supports more than one mode. The higher-order mode has a larger mode-field diameter than the primary mode, and hence it experiences more bending loss. But, as the wavelength approaches 808nm, the extra mode carries less energy since the primary mode begins to carry more energy. Consequently, the signal loss due to the extra mode decreases and so there is a drop in attenuation just before the λ_{ce}. After the λ_{ce}, the fiber can only support one mode and so the attenuation is only due to the primary mode. Hence, the experimental values obtained in this thesis work are in a good agreement with the theoretical expectation.

According to equation (1.0.1) the MAC factor of optical fiber depend on MFD and λ_c. And also from equation(2.6.1) cut off wavelength is 2.2 μm for $n_1 = 1.4504$,$a = 4.15$ μm and $\Delta = 0.01$ for single mode fiber. According to spread sheet and manufacturing lists the MFD is given as follows in table 4.1. In my experimental analysis the numerical value of MAC factor in SMF at a fixed radius of curvature when the operating wavelengths of 532nm, 633nm, and 808nm is 1.6± 0.3, 2.3± 0.4, and 2.9± 0.4 respectively. So now it is also depend on the operating wavelengths i.e. the operating wavelength increases it is again increases.

Wavelength(nm)	$\lambda_c(\mu m)$	MFD(μm)
532	2.2	3.7 ± 0.6
633	2.2	5.1 ± 0.8
808	2.2	6.4 ± 0.9

Table 4.1: MFD for different wavelength

4.1 Data Error Analysis

There are many errors sources in power loss measurement. Those errors might be due to:

- Good coupling efficiency requires precise positioning of the fiber to the center the core in the focused laser beam. Since single mode fibers have got small core size, they require more elaborate couplers with sub micron positioning resolution of ± $5\mu m$. The focused spot could not be comparable to the core size. This is due to the numerical aperture (NA) used in the experiment is not as small as the NA of the fiber.

- Fluctuations in detected power

- The dependence of the detector responsive on the wavelength and direction of the incident light, and on the ambient temperature; the uniformity of the reponsivity; and the effects of the coupling in to the detector.

- Calibration of the detector and experimental set up
- Coupling effects such as multiple reflections. Even so, a measurement accuracy of ± 5%to ± 10% is all that can be expected in general.
- The uncertainty of the power measured by the power detector is 0.0001.

Chapter 5

Conclusion

In my experimental demonstration attenuation coefficient is proportional to the wavelength. More of the field has to travel faster than the velocity of light to maintain the wave front, and thus radiation loss occurs and again attenuation is inversely proportional to the bend radius. As the bend radius decreases the amount of the mode field that has to travel greater than the velocity of light increases. Thus, the attenuation of the optical signal increases.

To reduce the amount of attenuation in a bent SMF a few guidelines must be followed. First of all, bends in fibers that are smaller than 6cm in radius must be avoided next, the signal wavelength must be longer than the cut off wavelength since the appearance of high-order modes would result in an increase in attenuation. In the future, some improvement to this thesis can be made. First , the use of a more powerful light source would reduce the noise seen in the measured spectrum. Consequently, more precise results can be obtained since there would be a better signal to noise ratio and so more of the signal can be seen without distortions. Also, the bending loss of fibers from different manufacturers and of different designs can be compared to analyse the tolerance of different fibers to short bend radius.

As a whole the results from the experiment have suggested that the optical power loss due to bending at the visible spectrum is more apparent than loss due to other effects such as absorption and scattering.

Appendix A (experimental data)

Bending radius(cm)	Attenuation Coefficient (dB/m)
0.50	0.475
1.00	0.465
1.50	0.455
2.00	0.445
2.50	0.435
3.00	0.41
3.50	0.395
4.00	0.375
4.50	0.355
5.00	0.335
5.50	0.29
6.00	0.275
6.50	0.245
7.00	0.155
7.50	0.135
8.00	0.12
8.50	0.10
9.00	0.085
9.50	0.075
10.00	0.06
10.05	0.045

Table 5.1: Attenuation Coefficient, wavelength 532nm

Bending radius(cm)	Attenuation Coefficient (dB/m)
0.50	0.48
1.00	0.465
1.50	0.44
2.00	0.42
2.50	0.41
3.00	0.395
3.50	0.375
4.00	0.36
4.50	0.325
5.00	0.31
5.50	0.295
6.00	0.28
6.50	0.245
7.00	0.23
7.50	0.18
8.00	0.17
8.50	0.145
9.00	0.125
9.50	0.105
10.00	0.085
10.05	0.065

Table 5.2: Attenuation Coefficient, wavelength 633nm

Bending radius(cm)	Attenuation Coefficient (dB/m)
0.50	0.61
1.00	0.59
1.50	0.56
2.00	0.54
2.50	0.51
3.00	0.48
3.50	0.45
4.00	0.44
4.50	0.39
5.00	0.37
5.50	0.35
6.00	0.34
6.50	0.33
7.00	0.30
7.50	0.28
8.00	0.27
8.50	0.25
9.00	0.23
9.50	0.22
10.00	0.17
10.50	0.10

Table 5.3: Attenuation Coefficient, wavelength 808nm

Appendix B (Electromagnetic Spectrum)

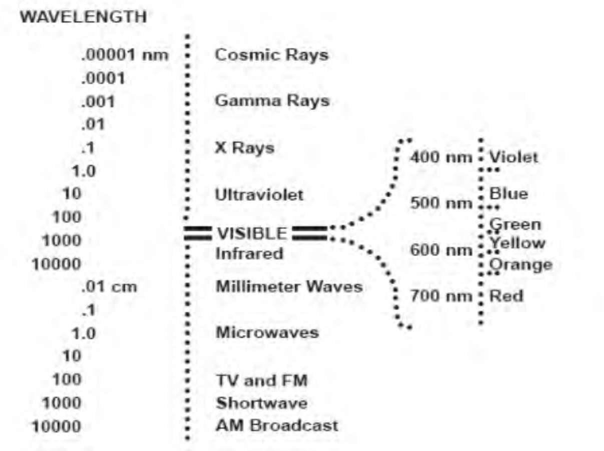

Figure 5.1: Electromagnetic Spectrum

Appendix C (Other loss Mechanism)

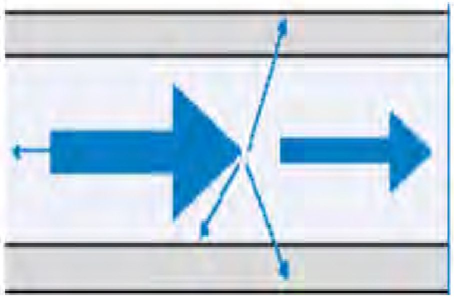

Figure 5.2: Loss due to Rayleigh Scattering

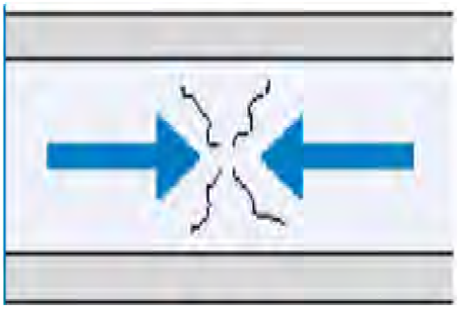

Figure 5.3: Loss due to Absorption

Bibliography

[1] A.M.Agarkar, Novel Single Mode Fiber Ultra Low Loss Design in 1550μM Window considering PMD,DGN and various Bending radii,volume 10, No 7,PP 29-33, 2010

[2] C.Unger and W.Stcklein, Investigation of the Microbending Sensitivity of fibers, Journal of Lightwave Technology, Vol 12, No 4; pp 591-596,1994

[3] Susanna Cattelan, Marco Ruzzier, Martino Travagnin,Macrobending Loss in Bend Insensitive Fibers: A Statistical Parameter volume 5; No.12; PP 258-262 2007

[4] Fedor Mitschke,Fiber Optics physics and technology,Heidelberg Dordrecht London Newyork PP 346; 2009

[5] ALEXIS MENDEZ, Specialty Optical Fibers Handbook,MCH Engineering, LLC, Alameda, California T. F. MORSE,Photonics Center, Boston University, Boston, Massachusetts PP 29-30,34; 2007

[6] Gerd Keiser,Optical fiber communications, second edition.GTE communications systems Division, Tokyo PP 93; 1991

[7] Gerard Kuyt, Piet Matthijsse,The impact of new bend-insensitive single mode fibers on FTTH connectivity and cable designsVol 12, No 4, pp.591-596, 1994.

[8] A.Joyghatak K.Thyagarajan,Introduction to fiber Optics,PP 195; 1998

[9] R. Morgan, J.S. Barton, P.G. Harper, and J.D.C. Jones, Wavelength dependence of bending loss in monomode optical fibers: effects of the fiber buffer coating, Optics Letters, Vol.15, No. 17, PP 29-35, 1990

[10] Ginu Rajan (Thesis) Dublin Institute of Technology A macro-bend fiber based wavelength demodulation system for optical fiber sensing applications (2008).

[11] Jerry D. Gibson, The Communications Hand Book,Second Edition,Editor-in-Chief ,Southern Methodist University,Dallas, Texas pp 599-609; 2002

[12] Govind P Agrawal,Non linear fiber Optics, fourth edition academic press 84Theobal's London WCIX 8RR,UK, PP 27; 2007

[13] Govid .P.Agrawal,Fiber Optic communication systems, third edition (Wily series in microwave and opticalengineering kai Chang series editor) PP 53-54, 55-58; 2002

[14] A.J. Harris, and P.F. Castle, Bend loss measurements on high numerical aperture single-mode fibers as function of wavelength and bend radius, Journal of Lightwave Technology, Vol.4, No. PP.45 1 1986

[15] Joseph C.Palais Fiber Optic Communication Fifth edition(House of electronics Industry, Beijing) PP 132-135; 2009

[16] H. Renner, Bending Losses of Coated Single-Mode Fibers: A Simple Approach, Journal of Lightwave Technology, Vol. 10, No. 5,1992

[17] Hecht, Jeff. (1999). Understanding Fiber Optics (Third Edition). New Jersey: Prentice-Hall, Inc PP. 234; 2003

[18] IEC 60793-1-44, Ed.1: Optical fibres Part 1-44: Measurement methods and test procedures Cut-off wavelength; 2002

[19] Harry J R Dutton, Understanding optical communications, first edition PP 523, 1998

[20] D. Marcuse, Curvature loss formula for optical fibers,J. Opt. Soc. Amer. B, vol. 66, pp. 216-220, 1976.

[21] S C Gupta, Textbook on optical fiber communication and its applications (Prentice Hall of India (PHI) PP 245,2004

[22] R. T. Schermer and J. H. Cole, Improved bend loss formula verified for optical fiber by simulation and experiment, IEEE J. Quantum Elect., 43, 899-909 2007.

Declaration

I, the undersigned, declare that this thesis is my original work and it has not been presented before for a degree in any other University. Moreover, I declare that all the sources of material used for the thesis have been dully acknowledged.

Name: Mekuanint Lemlem

Signature:– – – – – – – – – – – –

This thesis has been submitted for examination with my approval as
University advisor.

Name: Prof.A.V.Gholap

Signature:– – – – – – – – – – – –

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