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Analysis of bending losses in single-mode optical fiber for determining optical signal quality

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ABSTRACT

Optical fiber is an advanced transmission medium composed of glass fibers, offering significantly higher data transfer speeds compared to conventional electrical cables. This study aims to analyze power loss resulting from bending in single-mode optical fibers (SMF) to assess the impact on optical signal quality. Five distinct SMF types were simulated using OptiFiber software at wavelengths of 1310 nm and 1550 nm, with bending radii varying from 20 – 46 mm in increments of 2 mm. The results demonstrate that power attenuation in optical fibers is affected by the wavelength of operation and bend radius. At a wavelength of 1310 nm, the highest material loss was recorded in SMF-28 at 0.0125 dB/km, whereas at 1550 nm, SMF-28 exhibited the highest material loss of 31.963 dB/km. Moreover, an increase in bending radius results in a reduction of bending losses, while a decrease in bending radius leads to a significant increase in losses. These insights contribute to the development of improved fiber optic cable designs by advocating the use of enhanced protective shielding to mitigate bending-induced signal degradation.

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1. INTRODUCTION

The rapid advancement of telecommunications technology has necessitated the optimization of transmission media to enhance data transfer capacity and efficiency. Transmission media serve as a conduit for the exchange of information over long distances. Among various technological developments, fiber optics have emerged as a superior transmission medium due to their high bandwidth capabilities and immunity to electromagnetic interference [1].

The latest and fastest transmission medium for passing data from transmitter to receiver is optical fiber. Fiber optic cable is a cable made of glass fibers that have advanced technology with faster data transfer speeds than regular cables. Compared to other types of cables, fiber optic cables are relatively expensive, but have longer range, from more than 550 meters to hundreds of kilometers, resistant to electromagnetic interference, and can transmit data at higher speeds, compared to other types of cables. Optical fiber is a cutting-edge transmission medium that utilizes light signals instead of electrical signals, enabling superior data transmission speeds, lower attenuation, and resistance to external electromagnetic disturbances [2].

Optical fibers have advantages over other transmission media, so they become the main means to fulfill the needs of modern telecommunications technology [3]. One type of telecommunication optical fiber that is widely used today is single-mode fiber (SMF). SMF is an information transmission device utilizing light, characterized by one refractive index and lacking propagation along the medium. Light that can only light with wavelengths of 1310 nm or 1550 nm is transmitted [4]. Compared to conventional copper cables, fiber optics provide longer transmission distances and improved signal integrity. SMF is widely used in modern telecommunications due to its high transmission bandwidth, reduced modal dispersion, and compatibility with integrated optical technology [5].

Several studies have highlighted the superior performance of SMF in minimizing signal loss and maximize data transfer rates. Research has shown that SMF can transfer data 50 times faster and further compared to fiber multi-mode. The smaller cores used in SMF reduce the interference that the caused by distortion and overlapping light pulses, thus making it more reliable, stable, fast, and suitable for long-distance communication [6]. Despite these advantages, SMF performance is significantly affected by bending loss, which has been extensively studied in various research contexts. Some studies have investigated macro- and micro-bending losses separately, while others have explored general attenuation mechanisms in optical fibers [7]. However, there remains a gap in comprehensive modeling of bending losses using commercially available refractive index profiles at 1310 nm and 1550 nm [8].

Bending loss in optical fibers occurs due to structural deformations, which alter the refractive index and angle of incidence of light within the fiber core. Bending effects are generally classified into macrobending and microbending losses [9].

Macrobending losses occur when the fiber experiences large-radius bending, leading to light leakage into the cladding [10]. Bending can be caused by unintentional factors that result in the direction of propagation. The light inside the optical fiber bends away from the direction of incidence of the light exiting the core, but exits the optical fiber towards the cladding [11]. Microbending losses are caused by microscopic effects due to defects in the core and limit cladding. The defect is caused by the manufacture of the cable which is not good, error cabling, low temperatures, or certain stresses on some fibers. Disadvantages micro-bending is more difficult to detect because the bending radius is close to the core radius fiber, resulting in intermode power coupling. Microbending losses can reduced by using a flexible fiber protection jacket [12].

Optical signals are dampened due to bending which is affected by the radius of bending. This leads to decreased receive power and performance of the fiber optic communication system. Research previously by [12] found that bending in SMF causes macrobending losses. In five windings with a radius of 0.25 cm, the loss value for SMF is -12.73 dB, and for multi-mode in five-winding mode is -1.48dB, and for one-winding mode is 0.44 dB [13]. Addition, research conducted by [14] where the bending of SMF causes an average power loss of 0.11 dB at 20 mm radius, 0.05 dB at 30 mm radius, and 0.02 dB at 40 mm radius [14]. Research data [13] shows that the model used is a model of equivalent evaluation or equivalent evaluation model with all fibers having the same wavelength the same. The bending radius ranges between 0.5 mm and 2.5 mm, and the position of power loss which is calculated proportional to the length of the straight fiber equivalent to the bending radius 0.5 mm. At a bending radius level of 0.5 mm, the power loss is 17.20 dB, and the level of the larger bending radius gradually decreases up to 2.64 dB [12].

This research aims to overcome these problems by modeling the following SMF under various bending conditions to analyze the power loss due to bending. The purpose of this study is to determine the quality of the optical signal and ensure the performance of the network optimal optical fiber, thus supporting stable and effective data communication in the system integrated fiber optic communication.

2. MATERIALS AND METHOD

2.1. Materials

This research was conducted through simulation using a laptop device ASUS 5, OptiFiber software version 2.1.0.133, and an OptiFiber dongle with serial #OCF-2011-. 309H to design and simulate SMF bending on samples SMF-28, SMF-28e, SMF-28e+, SMF-28e+LL, and SMF-28ULL. The core and cladding radius were consistently maintained at 4.1 µm and 62.5 µm, respectively, across all fiber types.

2.2. Methodology

Identification of losses due to bending is done by determining the SMF profile based on the refractive index and radius profiles in region 0 and region 1.The research begins with the selection of the type of optical fiber to be studied, namely SMF-28, SMF-28e, SMF-28e+, SMF-28e+LL, and

SMF-28ULL. Each of these fibers was characterized based on the core and cladding values, as well as the corresponding optical fiber profile. The main materials that used is pure silica with the addition of dopants in the form of germanium and florin for forming the optical fiber dispersion model. Furthermore, parameters such as mode field diameter and the cut-off wavelength is determined for each fiber type.

Bending loss simulations were performed with two approaches, namely microbending and Macro. For macrobending, models from Sakai and T.Kimura were used with variations of bending radius between 20 mm to 46 mm. The results of this simulation were analyzed at a length of 1310 nm and 1550 nm waves to identify the level of power loss that occurs due to optical fiber bending. The design process begins with determining the index profile refractive index of optical fibers using the Refractive Index Profile feature on OptiFiber. Refractive index for the core and cladding are inserted according to the parameters listed in. The dispersion model is determined by selecting the material in the Material Properties menu. Pure silica is used as the base material, while germanium (3.1%) and florin (1%) are used as the dopants to modify the optical characteristics of the fiber.

Fiber mode simulation was performed using the matrix method for LP Modes. The results of this simulation are displayed in the form of a mode field graph, which is shows the light field distribution inside the fiber. To determine the wavelength cut-off, additional simulations were performed using LP_{01} and LP_{11} modes, with theoretical results of shows a cut-off wavelength of about 1.3164 µm. Bending loss simulation is done by inputting the bending radius parameter into the OptiFiber application. The Sakai and Kimura model is used to analyze power loss due to macrobending, where parameters such as bending radius, wavelength light, and the difference in refractive index between the core and the sheath affects the size of the loss power. Bending with a smaller radius tends to produce less power loss is larger, as light escapes the fiber core more easily.

Fiber modes with LP Modes (matrix method) at specific wavelengths are matched with the diameter of the mode field, resulting in a mode index without a cut wavelength off. The simulated cut-off is obtained from the Matrix Method mode which is then recalculated to shows the mode parameters of LP_{01} optical fiber. Determination of fundamental mode properties was performed using material and loss parameters, by varying the radius of the from 20 mm to 46 mm for the bending parameter resulting in loss. In the section wavelength is adjusted with a choice of values from 1.2 to 1.6 with 100 iterations. Bending loss simulation, in microbending, A value less than 1 and p value around 2 were used. In macrobending, model 1 was selected, namely J. Sakai and T. Kimura with a radius of varies from 20 mm to 46 mm.

3. RESULTS AND DISCUSSIONS

3.1. Factors of SMF Bending Loss

Several critical factors influence bending losses in SMFs, including curvature radius, fiber type, fiber length, and operating wavelength. The bending radius has the most significant effect, as a smaller radius is associated with greater power loss [15]. These factors directly affect the optical signal quality and efficiency of optical communication systems. In addition, the angle of curvature, type of fiber optic material, and environmental conditions such as temperature and humidity also play a role in affecting the degree of power loss due to curvature. Signal propagation mode and signal polarization also determine the amount of bending loss that occurs [16]. By understanding the factors that affect power loss in SMF, the design and optimization of efficient and high-quality optical communication systems can be done more easily and effectively.

3.2. Analysis of Power Loss Due to Bending in SMF with Variation of Bending Radius

The bending loss analysis of the SMF shows that bending radius, optical fiber type, fiber length, and wavelength are factors that significantly affect optical signal quality. Bending loss can markedly rise as the bending radius diminishes, hence impacting the effectiveness of the optical system of communication. This research was conducted to minimize losses by modeling optical fibers with wavelengths of 1310 nm and 1550 nm commonly used in telecommunications, with a bending radius variation of 0.020 m to 0.046 m, and using 5 types of SMFs namely SMF 28, SMF28e, SMF 28e+, SMF 28e+LL, and SMF 28 ULL. This analysis underscores the necessity of designing and optimizing an efficient, high-quality optical communication infrastructure. This simulation produces data that can show the magnitude of power losses due to bending in the SMF caused by external factors. The mode field diameter (MFD) is the area through which light enters the core and sheath. During bending, a reduced MFD diameter (< 8 μm) results in heightened power loss due to enhanced interaction among light as well as the fiber wall. Recent study indicates that the MFD is optimum when the diameter ranges from 8 to 10 μm, hence minimizing bending loss at 1310 nm [17].

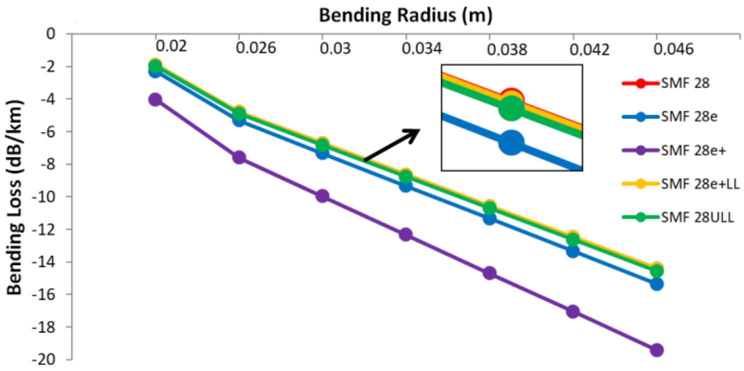

Figure 1. Bending losses for wavelength 1310 nm.

The results of the bending radius variation can be seen in Figure 1. where the bending radius greatly affects the power loss of the SMF. The graph shows almost constant bending power loss at all bending radius. The smaller the bending radius, the greater the power loss. When the SMF is bent with a certain radius, it causes the inside of the optical fiber to become tighter and the outside of the optical fiber to be stretched, resulting in changes in the density of the optical fiber core and cladding material. The alteration in material density induces variations in the refraction index of both the core and the cladding as a result of optical stress effects [18]. Although the principle of total internal reflection applies to light rays in an optical fiber, the intensity of light decreases as it travels through the optical fiber from end to end. This indicates the presence of light loss during propagation. The bending of optical fiber at a specific radius can alter the trajectory of light propagation, resulting in some light beams entering the sheath [19]. The varying bending radius of each SMF has a different bending loss value. This is due to the distinct refractive indices and normalized frequency values of each SMF, leading to varying light power transmission speeds throughout the SMFs.

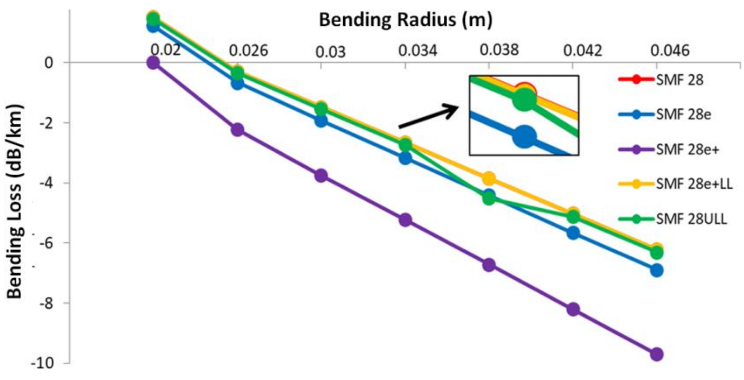

Figure 2. Bending losses for a wavelength of 1550 nm.

The results at a wavelength of 1550 nm are much higher than the results at a wavelength of 1310 nm (see Figure 2). The radius of bending is directly related to the wavelength employed; thus, a shorter wavelength results in a smaller radius of bending [20]. The power loss caused by SMF bending results in the signal passing through the core experiencing loss. Light experiences maximum loss when the incident angle is smaller than the critical bending angle that occurs in the SMF [21]. The critical angle in this study is 60° for each SMF. Meanwhile, the smaller the bending radius value, the smaller the curvature angle, so the bending radius value is directly proportional to the curvature angle value. Changes in the refractive index of the core or cladding can be known from the propagation loss. A larger disparity in the refractive indices of the core and cladding results in increased propagation loss [22]. This indicates that wavelength is inversely related to energy. Each SMF possesses a distinct energy level, observable by the normalized frequency value associated with each SMF.

3.3. Effect of Bending Radius on Optical Signal Quality

SMF bending can substantially impact optical signal quality. SMF bending can lead to decreased light intensity, signal distortion, and data loss. This is due to changes in the fiber structure that affect the way light propagates [23]. The damage resulting from the bending of SMF encompasses light absorption by the fiber material, alterations in the refractive index, and heightened attenuation [24]. All of these factors can affect optical signal quality, thus having a significant impact on optical communication systems. A decrease in signal quality can cause data errors, reduce transmission speed, and even disrupt communication. Therefore, it is important to minimize optical fiber bending [25].

4. CONCLUSION

The power loss due to bending in the SMF is influenced by both the radius of the optical fiber and the wavelength. The wavelength in SMF plays an important role in ensuring that only one mode of light can propagate effectively, thus minimizing intermodal interference and improving optical signal quality. At a large bending radius, the 1550 nm wavelength has a smaller bending loss because its light field is spread more widely, thus keeping the light energy in the fiber core. Conversely, at a small bending radius, the 1550 nm wavelength may experience increased bending loss because its light field is closer to the cladding, making it easier for light energy to escape the fiber core. In this situation, some of the light energy may escape from the optical fiber. The same is true for the 1310 nm wavelength.

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