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ORIGINAL STUDY

Wide Band Single-Mode Optical Fiber Design for Decreasing Bending Loss

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ABSTRACT

Radiation loss due to fiber curving or bending is a major challenge in advanced technical applications like fiber-optic sensing or biomedical applications. This study focuses on the basic features that characterize a single-mode fiber (SMF) and its critical parameters in view of the recent improvements made. The planned design of SMF is, however, intended to resolve these problems by proposing minimizing bend loss by adopting a five-layer fiber structure designed to keep the optical field within the fiber core. The proposed SMF design exhibit ultra-low bending sensitivity, with estimated bending loss of 2×10^{-3} dB/turn for bending radius of 5 mm. The fiber is designed to operate over a wide communication band from 1.3–1.65 μm, hence demonstrating flexibility in its potential applications.

Keywords: Bending loss, Radius of curvature, Wrapping turn, Optical communication, Multi-layer cladding

1. Introduction

The field of communication has been revolutionized by this invention because signal detection and transmission over very long lengths is now possible without any reduction in data using the optical fiber [1]. Ultimately, however, the bending or curving of the fibers causes reduced signal intensity [2]. This is a challenging objective over various applications in different fields [3], e.g., health monitoring [4], and telecommunications [5]. While telecommunication has paved the way for a proliferation of information, it is not without its drawbacks [6]. Yet when the optical fiber bent or curved one last signal loss will occur as the rays of light are radiated on account of bending or curving these fibers. Therefore, it is significantly troublesome when it comes to applications which might require bending or curling of glass fibers in fiber optic or biomedical applications [7].

The sensitivity of optical fibers to bending or curving has been a topic of extensive research over the years. Researchers have investigated and proposed various solutions to control the bending losses using machine learning as depicted by Amiri I. et al. in 2019 [8], or minimize them improve the performance of optical fibers in applications where bending is unavoidable like Zendehnam et al. in 2010 [9].

Optical fibers are extensively used in modern telecommunication systems as they offer superior bandwidth and longer communication distances compared to traditional copper wires [10]. Bending loss is a crucial factor that limits the performance of optical fibers and has been treated in different methods [11]. For example, over large area, Li et al. in 2015, modified the design of a parabolic profile-single-mode fiber (SMF) with ultra-low bend sensitivity [12]. This aligned with Dhupar A. investigation in 2021 [13]. Previous Reports indicate that these fibers, which are designed to resist bending, can have minimum bend radii of 15 mm, indicating a 50% decrease in bend sensitivity when compared to conventional SMFs [14]. This results in greater fiber density and

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reduced bending loss, making them ideal for tight-access wiring and component installations necessary in fiber to home (FTP) applications [14]. In addition, these fibers have been shown to exhibit no additional attenuation loss when wrapped around a 30 mm diameter mandrel, which maintains signal strength. Optics needs to have less intrusive and space conscious enables like closures and terminations at customer premise. Behavior where light leaks from the core to cladding when bent and returns to the core when straightened became symptomatic for the optical power observed at the fiber [15]. However, during the bending process, the effective refractive index of the cladding becomes higher than that of the core, leading to a significant power loss in the cladding instead of coupling back into the core [16]. To prevent this cladding power leakage into the surrounding environment, it is crucial to ensure that the effective refractive index of the cladding at the bend is lower than that of the core. One method to achieve this is by incorporating multiple depressed index layers within the cladding structure. Therefore, we opted for a cladding structure consisting of five depressed index layers, which is relatively easier to fabricate and provides several parameters to control BL of the fiber. Furthermore, by minimizing the difference in mode field diameters (MFDs) between the proposed fiber and the conventional SMF during splicing, we can reduce the splicing loss. This study proposes a modified SMF design with a five-layer cladding structure, optimized for ultra-low bending sensitivity across a wide communication band (1.3 μm to 1.65 μm). The primary objectives of this research are:

1. To design SFM with five-cladding structure that minimizes bending loss.
2. To make sure that the proposed design is beneficial through simulations and experimental testing.
3. To demonstrate the significance of the design for any applications demanding high bend tolerance.

2. Materials and methods

2.1. Design and simulation

ZEMAX optical design program was what they used to finalize the design of SMF-28. Five thin films each of 1.464 refractive index and 65.77 Abbe number were developed for coating the fiber cladding. All this was meant to restrict the optical field only to the fiber core, therefore absolutely minimizing the power loss caused by bending. Normal investigations would most likely detect the bending loss (L) in a length (l) of SMF [17]:

$$\mathrm{L} = 10\log_{10}\left(\exp\left(2\alpha l\right)\right) \tag{1}$$

The bending loss coefficient α is determined by various factors, including the bending radius, the wavelength of light employed in the fiber, as well as the structural composition and material properties of the optical fiber [2]. Losses due to bending can often be disregarded when the bending reaches a critical radius of curvature (Rc) [18]. Rc is typically defined as:

$$\mathrm{Rc} = 3\mathrm{n}_2 \times \lambda / \left[4\pi(\mathrm{NA})^3\right] \tag{2}$$

In the given equation, Rc represents the critical bending radius (R), n_2 denotes the clad index of refraction, NA represents the numerical aperture of the fiber, and λ corresponds to the wavelength.

2.2. Experimental setup

SMF-28 fibers were used in the experimental verification, which have a typical core diameter of 9 μm with a tolerance of $\pm 0.5\,\mu$m and a typical cladding diameter of approximately 125 μm with a tolerance of $\pm 1\,\mu$m. The SMF length used was chosen from 2 to 5 m and belonged to the SMF 28 grade. An InGaAsP laser (IE-60825), operating at 1550 nm, was employed to measure fibers. The fibers had been wound around aluminum rods of radii from 4 to 15 mm, for every 1 mm increment. Bending loss was measured with the help of an Agilent 81635 power meter. The investigation included studying the effect of the number of turns (N), with a maximum of 40 turns examined. To ensure accuracy and reproducibility, each measurement set was repeated, and multiple tests and calculations were performed to validate the measured results. Fig. 1 illustrates a schematic diagram of the experimental setup for measuring bending loss.

3. Results and discussion

The simulations conducted using the ZEMAX optical design software revealed that the proposed 5 cladding structure substantially reduces bending loss compared to conventional SMFs at a bending radius of 5 mm the proposed design achieved an ultra-low bending loss of 0.002 dB/turn representing a tenfold reduction relative to standard SMFs designs. this marked improvement is attributed to the enhanced confinement of the optical mode within the core which is facilitated by the multi-layer cladding structure.

Fig. 1. A schematic diagram illustrating the optical configuration employed to measure BL of the fiber.

4. Multi-layer cladding

To highlight the superiority of the five-cladding coated SMF structure over the original SMF with a single cladding, an analytical comparison of their bending losses is presented in Fig. 2 and Table 1. The fiber parameters were adjusted to achieve a cutoff wavelength (λ_c) of 1.22 μm. The results demonstrate a significant reduction in bending loss with the introduction of more trenches, leading to a reduction factor of 10^6 to 1.55 μm. Substantial decrease in the losses due to bending is mainly due to the participation of trenching process, which decreases the effective cladding index for better confinement of the light. This in turn minimizes energy loss at the core-cladding interface, thereby improving waveguide performance in a variety of different applications. By effectively lowering the effective index of the cladding, trenching achieves refined control and confinement of the optical mode inside the waveguide core [19]. Consequently, this confinement greatly reduces the bending losses, which refers to the loss of optical power at the boundaries between the core and the cladding. The findings of the current study aligned with those reported in a recent investigation on multi-layer cladding fibers for high power laser delivery by Nishad E. et al. in 2024 [20]. The referenced study demonstrated that a triple-layered cladding configuration significantly reduces bending losses by an order of "2" compared to double layered cladding designs achieving a minimum leakage loss of 5.82×10^{-5} dB/km at a wavelength of 1.06 μm. Additionally, the study highlighted a minimal bending induced loss of 9.00×10^{-4} dB/km at a R = 14 cm.

5. Bending radii

To investigate the bending losses and its variation, the impact of the R was examined. Prior to subjecting the optical fiber to bending, the initial transmitted optical power was accurately measured. In Fig. 3, it is evident that there is a decrease in loss as R increases. However, beyond a certain point, the expected

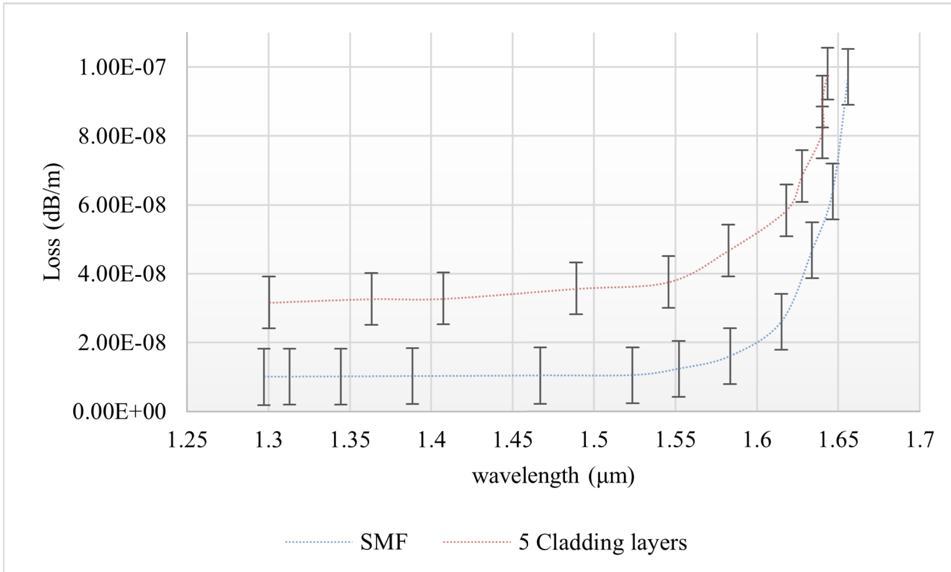

Fig. 2. For bending studies, fibers in structures that have single claddings have been compared with fivezoned fibers. The parameters compared included $\Delta n = 0.016$, 4.33 mm core diameter, $\lambda_c = 1.22$ mm, MFD = 5.22 mm, and R = 5 mm.

Table 1. Bending losses of SMF and 5 cladding coated SMF in dB/m.

Wavelength	SMF Bending losses in dB/m	Wavelength	5 Cladding layers Bending losses in dB/m
1.297	1.00E-08	1.300	3.16E-08
1.313	1.00E-08	1.363	3.27E-08
1.344	1.01E-08	1.407	3.27E-08
1.388	1.02E-08	1.489	3.56E-08
1.467	1.03E-08	1.546	3.75E-08
1.524	1.05E-08	1.582	4.67E-08
1.552	1.23E-08	1.618	5.84E-08
1.584	1.60E-08	1.628	6.83E-08
1.615	2.60E-08	1.640	8.10E-08
1.634	4.67E-08	1.640	9.00E-08
1.647	6.39E-08	1.643	9.81E-08
1.656	9.72E-08	1.643	9.81E-08

reduction in loss is not observed, and instead, an oscillation behavior of the loss with respect to the radius of curvature is observed. Based on these findings, one can depend on the semi-empirical equation shown below that establishes a relationship between L and R.

$$L = 5F1\,(5F2 + F3) \tag{3}$$

where F1, F2, F3 are exponentially related to the effective radius of curvature.

In the same figure, the solid line represents Eq. (3), which demonstrates good agreement with the experimental data. While the relationship between L and R may exhibit an exponential decrease, the presence of oscillations in the loss curve prevents the application of a simple exponential equation or model. This is observed in numerous previous studies, i.e., the sinusoidal and elliptical shaped bending configurations observed in 2021 by Mohd N. et al. [21]. This phenomenon can be attributed to the coupling between the fundamental propagation field, either through the core and clad structure or the protective coating layers [22], commonly referred to as the whispering-gallery mode [23]. Even for partial curves, the oscillatory behavior of the bend loss curves can be explained by the influence of thin films on lateral leaky mode radiation [24]. Consequently, a straightforward model suitable for rapid bending loss calculations cannot be employed when considering a broad range of R, particularly at low R values. Instead, Bessel functions, often of the first order, are commonly used. The reduction in bending loss in the proposed design enhances the performance of fibers in optical communications and expands their use for structural health monitoring. For example, the low loss can improve the sensitivity of crack detection systems in hydraulic concrete structures [25], enabling accurate detection of deformations, and confirms the design flexibility for diverse engineering applications. Such modifications have potential applications in advancing sensing technologies as indicated by Lu P. in their investigation in 2019 [26]. This aligns with prior studies, such as those focusing on the design modification of fiber-optic bends carried out by Azura N. and colleagues in 2020 [27]. Additionally, distributed optical fiber sensing system that rely on maintaining signal integrity over extended distances and under variable bending conditions proposed by Saktioto et al. in 2021 [28], would benefits from the ultra-low bending loss achieved by the

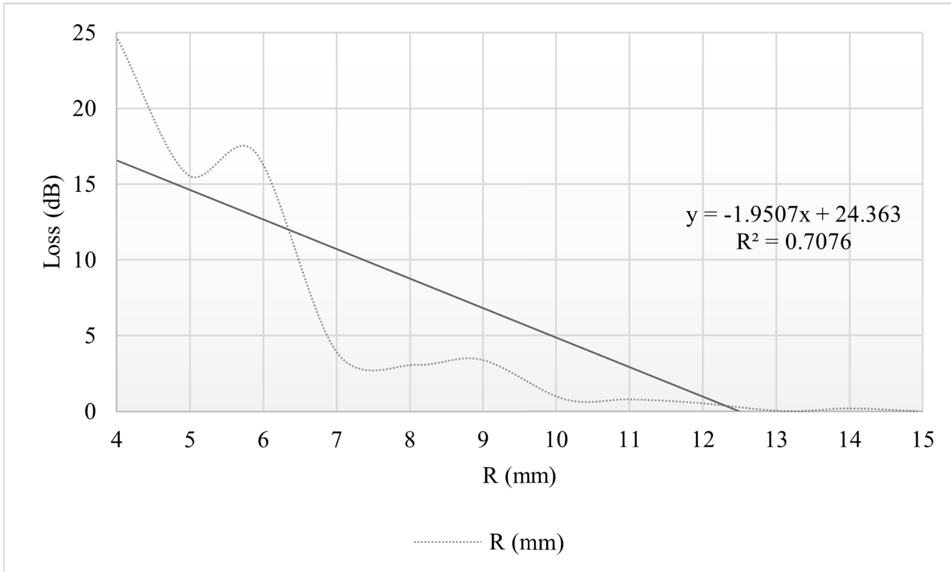

Fig. 3. Linear relationship between L and R. The average loss rate decreases per unit increase in radius.

proposed design. These findings emphasize that smaller bending radii result in higher levels of L. Finally, Fig. 3 underscores that the proposed SMF design able to reduce L, particularly for R > 10 mm. The linear regression represented by "y" equation highlights that L values decreased by approximately 1.95 dB for every 1 mm increment in R.

6. Number of turns

To investigate the impact of bending turns on optical fibers, an experiment was conducted by coiling optical fiber around aluminum mandrels. The study involved up to 40 turns. The results revealed two distinct patterns of bending as a function of the number of turns. The relationship L and N is illustrated in Fig. 4 for R ranging from 10 to 15 mm. We refrained from using R values below 4 mm for two primary reasons. Firstly, at very low R values, L experienced was exceptionally high. Additionally, when dealing with optical fibers, the presence of microcracks becomes a significant concern, especially when subjected to a very low radius of bending. Such microcracks can lead to problems and negatively impact the overall performance of the fiber. Conversely, when utilizing a radius greater than 15 mm, the attenuated signal affected by the fiber bent decreased significantly, resulting in minimal loss. Consequently, using measurements with R values exceeding 15 mm would yield inaccurate results, making it necessary to neglect the loss in those cases.

We observed a direct correlation between the loss and the number of turns in the bending process, with the slope of the correlation influenced by the radius of curvature. The relationship between the L and N can be described by a linear function, as depicted in Eq. (4) [18]. This linear function effectively captures and aligns with our experimental findings.

$$L = A + BN \tag{4}$$

Both parameters A and B exhibit a decreasing trend as R increases. However, the oscillatory relationship between L and R also influences these parameters, causing them to demonstrate similar behavior.

The measurement associated measuring the loss of bending ranged between 4 and 9 mm and the relationship between L and N were plotted. Initially, the loss was observed to increase linearly with the number of turns. As the number of turns increases further, the loss increased. But over a certain range, the loss seemed to be unaffected thereafter. Particularly, at very low resistance (about 4–5 mm), high increments in losses were seen. Fig. 5 shows the variations of L vs. N when R lies between a minimum of 4 and a maximum of 8 mm.

Optimizing the performance of optical fibers can indirectly benefit many biological and medical applications. The enhanced sensitivity and accuracy of optical sensors used in environmental monitoring [29], medical diagnostics and surgical treatments may lead to better health outcomes by improving disease detection [30], more effective treatments, and better monitoring of biological systems [31]. The results in this study indicate a significant reduction in bending loss as the bending radius increases.

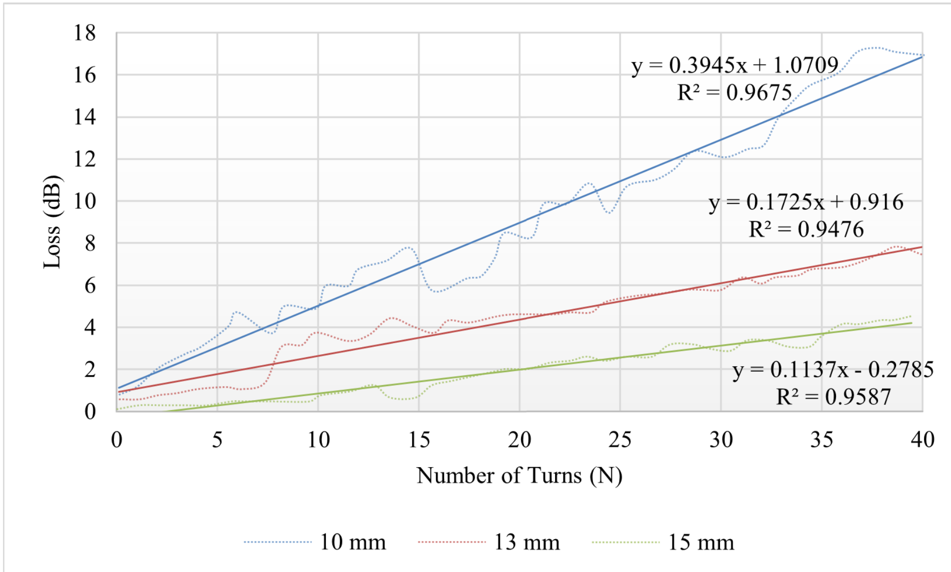

Fig. 4. The relationship between L and N within the range of 10 to 15 mm for the radius (R). R^2 value for all cases close to 1 indicate a strong linearity between L and N of each radius.

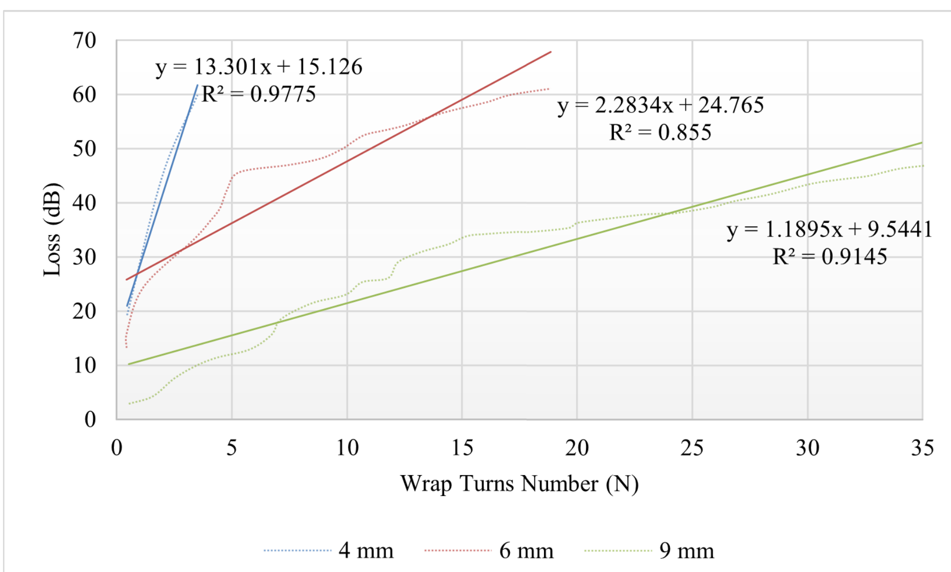

Fig. 5. The relationship between the wrap number of turns (N) and BL for a range of values from 4 to 8 mm for the radius (R).

This trend highlights the critical role of R factor to determine the SMF performance. The findings of this study are further supported by Thongdaeng and Worasucheep findings in 2016 [32], which demonstrate the insertion loss changes at smaller R of about 7.5 mm and negligible for larger radii (R > 15 mm).

When the optical fiber bends, the light inside the fiber does not become strictly confined to the total internal reflection, and some light may escape, resulting in loss of curvature [33]. In some cases, this can be considered a kind of diffraction effect, where the light bends around the fibers and partially escapes at angles. The amount of light lost due to bending can be reduced by designing the fibers with geometric shapes or special coatings to reduce this loss. While Fraunhofer diffraction as a specific phenomenon, involving diffraction in the far field of openings and obstructions [34], does not usually constitute the predominant effect in optical fibers, many related principles, such as pattern propagation, overlap, bending losses [35], and fiber face diffraction, can produce diffraction-like behaviors [36]. In addition, fibers can take advantage of diffraction principles in advanced devices such as Bragg fiber grids [37], and photonic crystal fibers [38], where cyclic structures within the fiber or at the fiber end work similarly [39].

7. Conclusion

Five-cladding structure SMF-28 was designed by ZEMAX optical design program by coating the internal face of cladding layer by inserting five thin films that have refractive index of 1.464 and Abbe number of 65.77. The theoretical analysis demonstrates that BL can be reduced to below 0.002 dB/turn at a wavelength of 1.55 μm for a single turn with a radius of 5 mm. To investigate BL variation in SMF across a range of bending radii 4 to 15 up to 40 turns, we conducted experiments. The experimental results show a reduction in loss with an increase in the curvature radius, and an oscillatory behavior of the loss against R was observed. The reason behind this behavior can be ascribed to the interaction of the fields between the core, cladding, and the coating layer, along with the interferences between the coating and the surrounding air. These interactions lead to re-injection and consequently produce two separate peaks in the observed phenomena. Consequently, a straightforward model that relies on a gradual decrease in loss with R is inadequate to account for these findings. We propose a semi-empirical relationship based on the experimental data, which exhibits good agreement. When examining the variation of loss against N, the results can be divided into two parts: one for reduced bending radii ($R \leq 9$ mm) and another for high bending radii ($R \geq 10$ mm). This differentiation is because of the variety in behaviors observed in these two regimes. We have derived equations to describe these measurements, and they provide a good and satisfactory fit to the experimental data.

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Conflict of interest

The author declares that there is no conflict of interest.

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