Optical Fibers Characterization for Macrobending Sensors

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The article delves into characterizing macrobending losses in optical fiber coils for use in diverse sensors. It examines Single-Mode Fiber (SMF) and Multimode Fiber (MMF) with step and graded index profiles incorporated into sensor coils of varying diameters and numbers of turns. The experimental configuration involves compressing the coils to monitor optical power loss caused by attenuation. The findings reveal that SMFs experience more significant macrobending losses than MMFs, while the graded index fiber exhibits notable resistance to bending. These results offer valuable guidance for fiber selection and sensor design considerations.
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In recent years, optical fiber sensors have garnered considerable attention due to their exceptional sensitivity, versatility, and durability. Optical fiber sensors emerge as a promising alternative, particularly in explosive environments where electronic sensors pose risks. Macrobending fiber sensors stand out as they are cost-effective and easily interrogated. They have found applications in various areas, such as sleep monitoring, breathing analysis, and vibration measurement. Macrobending occurs when an optical fiber is bent, causing some light to leak out of the core. The extent of this leakage depends on the bend radius, and the optical power loss serves as the sensor output. The design of such sensors relies heavily on the choice of fiber and sensor geometry, which significantly influence macrobending losses and overall sensor performance.

Hence, comprehensive macrobending data for different fiber types and bend diameters are crucial for effective fiber selection and sensor optimization. This study aims to characterize macro bend losses in fiber coils made from various fiber types, considering different coil diameters and numbers of turns. These parameters play a vital role in designing and optimizing macrobend fiber sensors. This research builds upon previous work focused on single-mode fiber and extends it to encompass multimode fibers, providing a broader understanding of macrobending behavior across different fiber types.

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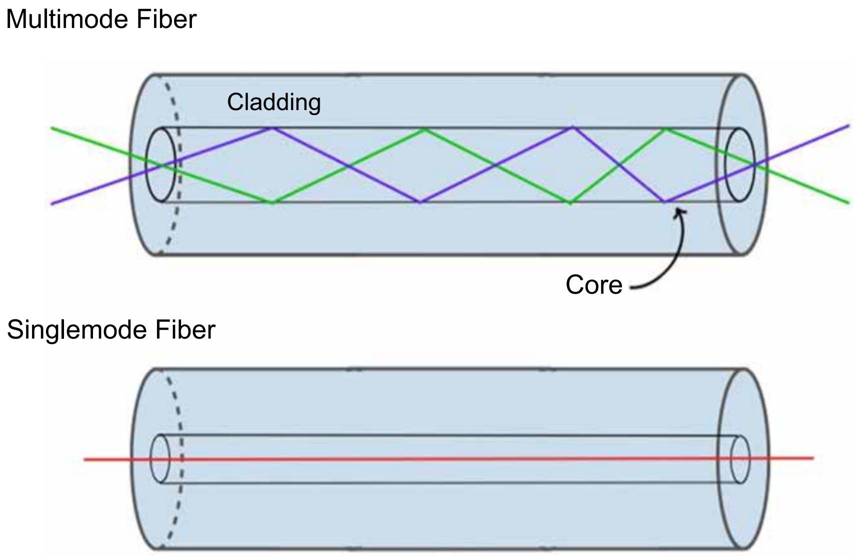
Fiber Types

There are two primary types of optical fibers: single-mode (SMF) and multimode fibers (MMF) (Figure 1). SMFs have a tiny core, usually around 9 micrometers in diameter, allowing only one light mode to travel through the fiber. This characteristic results in lower signal dispersion and attenuation. On the other hand, MMFs have a larger core, typically around 50 or 62.5 micrometers in diameter for telecommunication fibers and over 100 micrometers for sensor fibers. In MMFs, multiple light modes propagate through the glass, leading to modal dispersion and higher attenuation than SMFs. Additionally, communication fibers are optimized for specific wavelengths. MMFs operate at 850nm and 1300nm, while SMFs typically function within the wavelength range of 1310nm to 1625nm [6].

Fiber Profile Types

The profile of an optical fiber refers to the distribution of the refractive index concerning the radius of the fiber, which significantly impacts the

Figure 1. Different modes of propagation through a single-mode and a multimode fiber.



Source: Adapted from https://americanfibertek.com/2019/03/06/multimode-vs-singlemode-fiber/.

propagation of light within the fiber. An optical fiber typically consists of three main components: the core, the cladding, and, in some cases, an outer coating for additional mechanical protection [6] (Figure 2). The core is the central region for light transmission, while the cladding helps contain the light within the fiber. The first type of profile is the Step Index, characterized by an abrupt change in refractive index between the core and the cladding. The second type is the Graded Index, where the refractive index gradually changes from the core to the cladding [6]. In order to minimize macrobending losses, additional features are incorporated into the refractive index to create potential barriers that further confine the light fiel [7].

Macrobending

The phenomenon known as macrobending occurs when an optical fiber experiences a bending radius more prominent than 1 mm^2 [6]. When the fiber is bent, the light traveling through it may leak out of the core, leading to signal loss. This loss is directly related to the bending radius (Figure 3).

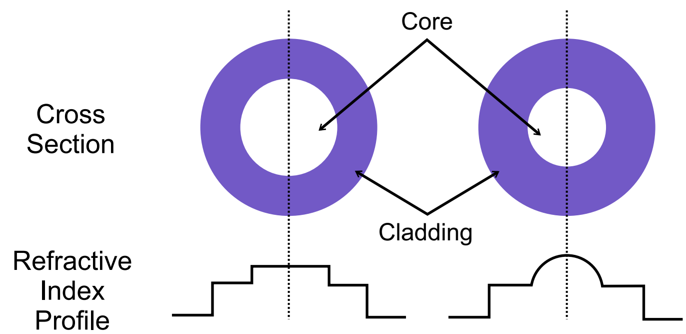
This mechanical characteristic of the fiber finds applications in various sensor types, including vibration, shape, and contact. The coil shape is particularly suitable for amplifying bending effects due to the overlap of fiber turns within the same volume. Therefore, it is crucial to characterize the profile of optical power loss in coils, considering parameters such as radius, number of turns, and curvature radius (Figure 4).

Reinsertion of Modes

Some optical fibers have a protective coating to shield the core and cladding. However, coated fibers can experience mode coupling issues caused by fiber bending. Bending or deformations introduce stress and alter the refractive index profile, leading to unintended interactions between modes. This phenomenon, known as mode coupling, causes light to transition from one mode to another, reinserting previously filtered-out modes and resulting in unexpected behavior.

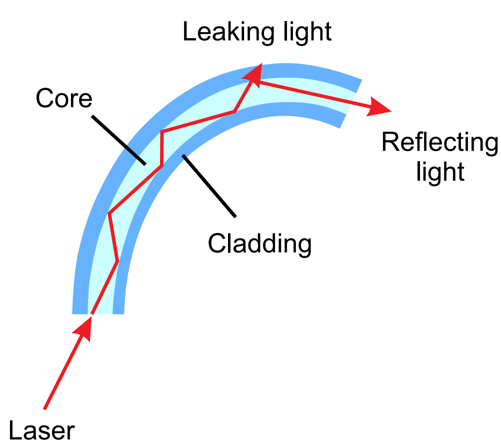
The degree of mode coupling depends on several factors, including the bending radius, fiber material, and light wavelengths. In coated single-mode fibers, oscillations observed in bend-loss curves are often attributed to the coupling between the fundamental mode and various whispering

Figure 2. Different fiber profile types.



Source: Adapted from https://www.fiberoptics4sale.com/blogs/wave-optics/step-index-optical-fibers.

Figure 3. Representation of optical power loss by bending radius [6].



Source: Adapted from Optical Fibers in the Design and Fabrication of Smart Garments–a Review [9]

Figure 4. The ideal shape for the fiber coil.

gallery modes, which are partially guided by the interface between the cladding and coating [8].

Materials and Methods

The macrobending losses of three different optical fibers were characterized. Fiber coils with a diameter of 40 mm and varying numbers of turns were constructed. The optical fibers tested included Single-Mode Fiber (SMF), Multimode Fiber (MMF) with a step-index profile, and a bend-insensitive graded index MMF.

The SMF used was CORNING-SMF-28e+, tested with four different coils having distinct numbers of turns (1, 5, 20, and 30) and utilizing a laser operating at a wavelength of 1560 nm. The MMF with a step-index used was FG105LCA from Thorlabs also tested with a coil of 30 turns but with different wavelength sources: a laser at 1560 nm and two LEDs operating at 940 nm and 650 nm. For the graded index MMF (model GIF50E from Thorlabs), a bend-insensitive type was used as a reference, with the fiber coil having 45 turns and undergoing testing. Table 1 details the specifications for each fiber coil.

The experimental setup consists of two parallel plates connected to a translational stage. One of the plates remains stationary, while the other is movable. As the movable plate shifts, the coil is continuously compressed at a constant speed of 0.01 mm/s, reducing its radius from 40 mm to 11.5, resulting in macrobending losses. The sensor readings are sampled at a rate of 0.1 s (Figure 5).

Results and Discussion

Figure 6 displays the macrobending attenuation for fiber coils a, b, c, and d. These coils were made from the same SMF28-e+ SMF but with a distinct number of turns, as described in Table 1. Figure 6 shows a more significant attenuation as the number of turns of the coil increases, as expected.

The increased macrobending attenuation for the curves from the blue curve can be seen. Figure 7 shows a macrobending attenuation comparison for three types of fiber: the SMF28-e+, the FG105LCA - ThorLabs, and the GIF50E – ThorLabs.

The grey curve presents the attenuation for the h fiber coil, which is made of the bend-insensitive graded index fiber. The results show that the unique index profile effectively eliminated bending loss for the conditions tested. The yellow, red, and blue curves represent the coils g, f, and e, respectively, with different wavelengths but the same fiber step index MMF. For the coil g, it is possible to observe that the curve for the MMF with the laser of 1560nm is noisier compared to the same fiber with the LEDS and SMF in the same wavelength. This may have occurred due to lower light coupling in the fiber coils e and f, which degraded the signal-to-noise ratio. When dealing with attenuation, there were no significant changes between the FG105LCA in different wavelengths. The figure also shows that the SMF fiber has a more significant attenuation than the MMF.

Conclusion

In conclusion, this article has successfully achieved its objective of characterizing

Table 1. Specifications of the tested optical fiber coils.

Coil	Fiber - Supplier	Type	Profile	Core diameter	Turns	nm – source
a	CORNING-SMF-28e+100Kpsi	SMF	Step Index	9 µm	1	1560nm (Laser)
b	CORNING-SMF-28e+100Kpsi	SMF	Step Index	9 µm	5	1560nm (Laser)
c	CORNING-SMF-28e+100Kpsi	SMF	Step Index	9 µm	20	1560nm (Laser)
d	CORNING-SMF-28e+100Kpsi	SMF	Step Index	9 µm	30	1560nm (Laser)
e	FG105LCA - ThorLabs	MMF	Step Index	105 µm	30	650nm (LED)
f	FG105LCA - ThorLabs	MMF	Step Index	105 µm	30	940nm (LED)
g	FG105LCA - ThorLabs	MMF	Step Index	105 µm	30	1560nm (Laser)
h	GIF50E - ThorLabs	MMF	Graded Index	50 µm	45	1560nm (Laser)

Figure 5. Experimental setup of parallel plates.

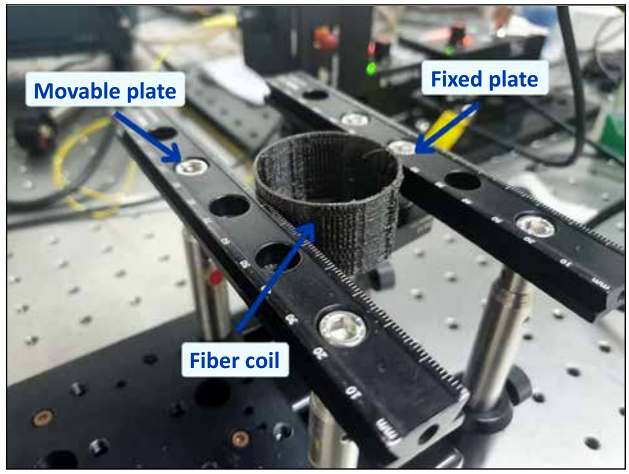
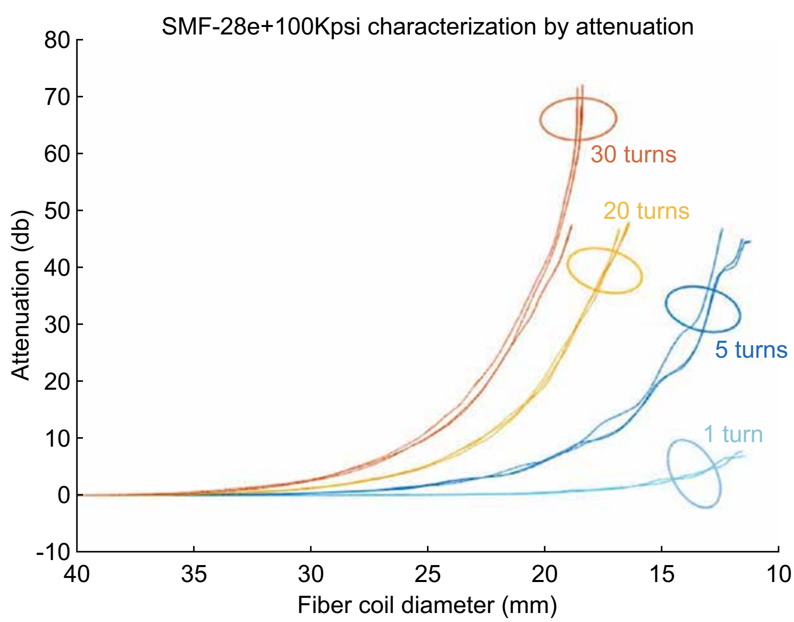


Figure 6. Attenuation is achieved by bending the radius and number of turns for the SM fiber.



Light blue – 1 turn, dark blue – 5 turns, yellow – 20 turns, and orange – 30 turns.

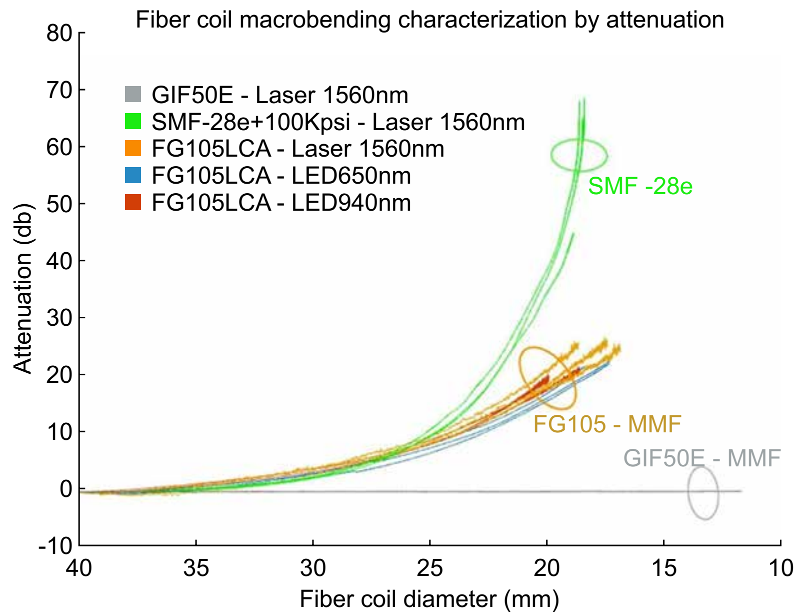
macrobending losses in fiber coils with different fiber types, providing a valuable tool for supporting the selection and design of macro bend-based sensors.

The experimental setup, which utilized two parallel plates to compress the fiber coils and observe the optical power loss due to macrobending demonstrated a direct relationship between bending radius and optical power loss.

The results indicated that Single Mode Fibers (SMFs) exhibited higher macrobending losses due to attenuation compared to Multimode Fibers (MMFs). Additionally, the attenuation increased as the number of turns in the coils increased. In contrast, the graded index fiber showed remarkable insensitivity to bending.

For future research directions, it is recommended to replicate the experiment using

Figure 7. Attenuation comparison between SMF and MMF.



different types of fiber and diverse wavelengths as light sources. Such investigations will contribute to a deeper understanding of the behavior of optical fibers under various conditions.

Acknowledgments

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References

1. Zhao T. Vital signs monitoring using the macrobending small-core fiber sensor. Wuhan: Optics letters, 2021.
2. Grillet A et al. Optical fiber sensors embedded into medical textiles for healthcare monitoring. IEEE Sensors Journal 2008;8(7):1215-1222.
3. Costa C. Non-electronic vibration sensor for automated inspection of industrial assets. Salvador: LARS, 2023.
4. Wang XY et al. Vibration sensing based on macrobending loss in a standard single mode fiber loop structure. Optical Fiber Technology 2019;48:95-98.
5. Costa C. Análise de curva de perda de potência ótica por Macrobending em bobinas de fibra ótica Monomodo. Salvador: SAPCT Cimatec, 2023.
6. Jay JA. An overview of Macrobending and Microbending of Optical Fibers. Nova York: Corning, 2010.
7. Bickham SR. et al. Theoretical and experimental studies of macrobend losses in multimode fibers. In: Proc. 58th Internat. Wire & Cable Symp 2009:450-457.
8. Renner H. Bending losses of coated single-mode fibers: a simple approach. Journal of Lightwave technology 1992;10(5):544-551.
9 King RR et al. Optical fibers in the design and fabrication of smart garments–a review. Fibres & Textiles in Eastern Europe 2022.