Macro Bending Losses in Single Mode Step Index Fiber

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Abstract : *Bending losses of power in a single mode step index optical fiber due to macro bending has been investigated for a wavelength of 1550nm. The effects of bending radius (4-15mm, with steps of 1mm), and wrapping turn (up to 40 turns) on loss have been studied. Twisting the optical fiber and its influence on power loss also has been investigated. Variations of macro bending loss with these two parameters have been measured, loss with number of turns and radius of curvature have been measured.*
This work founds that the Macro bending and wrapping turn loss increases as the bending radius and wrapping turn increases.

Keywords: *fiber optics, macro bending, loss, wrapping turn, single mode, multi mode, step index*

I. Introduction

The idea of using light waves for communication can be traced to as far back as 1888 when Graham Bell invented the photo phone in which sunlight was modulated by a diaphragm and transmitted through a distance of about 200 meters in air to a receiver containing a selenium cell [1].
Optical fibers were first envisioned as optical elements in the early 1960s [2]. It was developed in the early 1970s and is rapidly replacing traditional copper cable for transmitting information over hundreds to thousands of miles. Rather than sending data in the form of electrons, fiber optic technology uses photons, or light [3]. It is flexible, transparent made of extended glass (silicon) or plastic, slightly thicker than a human hair. It can function as a work guide or light pipe to transmit light between the two ends of the fiber.
Optical fibers are recognized as the superior medium for delivering high bandwidth communications signals over long distances. The key attribute that enables this performance is very low attenuation, i.e., signals experience very little power loss as they propagate along the length of the optical fiber. In 1970, Corning scientists produced the first optical fiber with attenuation *<20 dB/km*, i.e., less than *99%* power loss along *1000m* of fiber.

Optical fiber communication plays an important role in the development of high quality and high-speed telecommunication systems [4]. Radiative energy losses occur whenever an optical fiber undergoes a macro bend of finite radius of curvature. In the past a few years, there have been increasing efforts in reducing macro bending losses for single-mode step index fibers. Several fiber designs have been proposed to meet different macro bend loss requirements [5, 6]. The most important source of lose is the macro bending that occurs in the fiber-optic cable during installation or in the manufacturing process. When the fiber cable is installed and pressed onto an irregular surface, tiny bends can be created in the fiber cable. Light is lost due to these irregularities [7].
Objective of this basic research is:
To show the relationship between macro bending loss and bending radius in step index fiber
To show the relationship between macro bending loss and wrapping turn in step index fiber
To derive the mathematical expression for macro bending loss and to calculate the numerical values in step index fiber for different bending radius in the range 4mm-15mm

II. Methodology

Methods: we have implement Mathematica 5.1 and Origin 6.0 software. These two packages are used to generate data and plot graphs.

III. Results and Discussion

Optical confinement

Optical fibers work by confining and guiding [8, 9] the light wave within a long strand of glass by the principle of total internal reflection. Which are cylindrical dielectric waveguides made of central cylinder of glass with one index of refraction, surrounded by an annulus with slightly different index of refraction [10]. If the refractive indices of the core and cladding are n_1 and n_2 respectively, then for a ray entering the fiber, if the angle of incident (at the core cladding interface)θ_A, is greater than the critical angle, θ_C [11], then the ray will undergo total internal reflection at that interface.

Furthermore, because of the cylindrical symmetry in the fiber structure, this ray will suffer total reflection at the lower interface also and will therefore be guided through the core by repeated total internal reflections. This is the basic principle of the light guidance through the optical fiber.

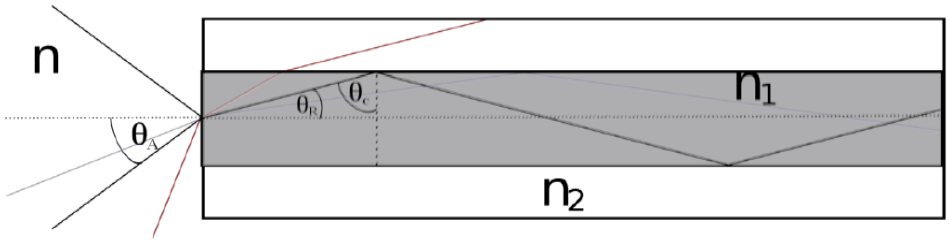

Fig. 1 A typical optical fiber waveguide consists of thin cylindrical glass rod [11]

Mathematically, Using Snell's law;

$$\theta_C = sin^{-1}\left(\frac{n_1}{n_1}\right) \qquad (1)$$

Where $n_1 > n_2$, n_1 is the refractive index of the core, and n_2 is the refractive index of the cladding.

Optical fiber

An optical fiber is long cylindrical dielectric structure usually of circular cross-section [12]. It is a flexible, transparent medium which are made of a pure glass (silica) not much wider than a human hair. It functions as a waveguide, or"light pipe", to transmit light between the two ends of the fiber[13].

An optical fiber consists of three concentric elements: core, cladding and the outer coating, is called protective jacket (plastic sheath). The core is usually made of glass or plastic. It is the light carrying portion of the fiber. The cladding surrounds the core. It is made of a material with a slightly lower index of refraction than the core. This difference in the indices causes total internal reflection to occur at the core-cladding boundary along the length of the fiber. Light is transmitted down the fiber and does not escape through the sides of the fiber. The jacket protects the fiber from external damage. The electromagnetic radiation is kept in the core by total internal reflection

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Types of fibers

An optical fiber is a dielectric waveguide that operates at optical frequencies. This fiber waveguide is normally cylindrical in form. It confines electromagnetic energy in the form of light to within its surfaces and guides the light in a direction parallel to its axis. The transmission properties of an optical waveguide are dictated by its structural characteristics, which have a major effect in determining how an optical Signal is affected as it propagates along the fiber.

Variation in the material composition of the core gives rise to the two commonly used fiber types. In the first case, the refractive index of the core is uniform throughout and undergoes an abrupt change (or step) at the cladding boundary. This is called a step-index fiber and can be divided into Multi mode fiber and Single-Mode.

IV. Single mode and multi mode fiber

The light waves propagate through the fibers in definite field configurations which are known as modes [13]. Based on how many modes are allowed to propagate in a fiber, it can be classified into multi mode fiber (MMF) and single mode (mono mode or fundamental mode) fiber (SMF) which support multi modes and single mode, respectively.

The core size of single mode fibers is small. The core size (radius) is typically around 4μm − 10μm. A fiber core of this size allows only the fundamental or lowest order mode, while high-order modes are lost in the cladding. Single mode fibers propagate only one mode, because the core size approaches the operational wave length.

SMF have many advantages, such as lower signal loss, a higher information capacity (band-width) than MMF, and low dispersion.

As their name implies, MMF propagate more than one mode. It can propagate over *100* modes. The number of modes propagated depends on the core size and numerical aperture (NA). As the core size and NA increase, the number of modes increases. MMF has the core radius bigger than *50µm*.

Step index and graded index fiber

In addition to modes, fibers are categorized based on the refractive indices of the material of the core which are step index and graded fibers.

Step index fibers which have the refractive index of the core *(n_1)* abruptly varies from the refractive index of the cladding *(n_2)* and the refractive index distribution of step index fiber is given by:

$$n(r) = \begin{cases} n_1, 0 < r < a \ , core \\ n_2 \quad r > a, cladding \end{cases} \qquad (2)$$

Where *r* represents the cylindrical radial coordinate and *a* represents the radius of the core

Here, *r* represents the radial distance from the fiber axis, *a is* the core radius; α is the dimensionless parameter which defines the shape of the profile, and Δ is the refractive index difference which is given by:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \approx \frac{n_1 - n_2}{n_1} \qquad (3)$$

Numerical Aperture

Numerical Aperture (NA) of the fiber is the light gathering efficiency of the fiber, and it is the measure of the amount of light rays that can be accepted by the fiber. It indicates the maximum angle at which a particular fiber can accept the light that will be transmitted through it.

The higher the NA of an optical fiber's,the larger the cone of light that can be coupled into its core. It is a dimensionless number that characterizes the range of angles over which the system can accept or emit light [14]. The fiber that uses its proper work, it is a requirement for light to successfully travel down an optical fiber, the light must enter the fiber and reflect off the cladding at greater than the critical angle. Due to the refractive index change the direction of the light as it enters the core of a fiber. There is a limit to the angle at which the light can enter the core to successfully propagate down the optic fiber. Any light striking the cladding at less than the critical angle will go straight through into the cladding and be lost. By applying Snell's law at the entrance of the fiber, NA can be related with refractive index of the fiber. It is derived from calculating the sine of the half angle (θ) of acceptance within the cone of light entering the fiber core.

$$NA = \sqrt{n_1^2 - n_2^2} \qquad (4)$$

Where n_1 is the refractive index of the core and n_2 is the refractive index of the cladding.

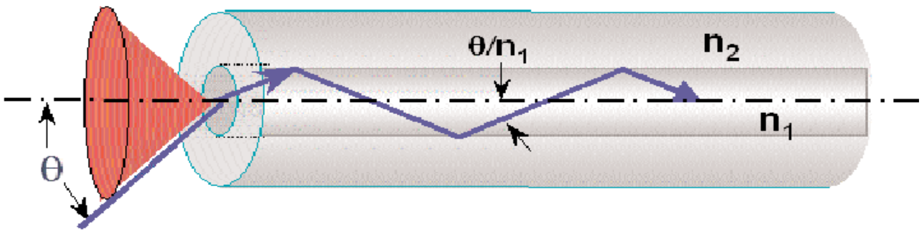

Fig. 2 Numerical Aperture defines the maximum angle (the cone of acceptance) at which light can be launched into a fiber [14]

Optical fiber losses

Losses of signal is a crucial parameter that should be considered in optic fiber communication. This is because it is a determining factor of cost of fiber optic telecommunication systems as it determines spacing of repeaters needed to maintain acceptable signal levels. This ensures quality and correct delivery of signals at the receiving end.

The overall attenuation pattern, a sum of attenuation contributed by the various loss mechanisms. Attenuation is a relative measure of the output to input intensity and is given by:

$$Attunation\left(\frac{dB}{Km}\right) = \frac{10}{L}\left(\frac{I_0}{I_i}\right) \qquad (5)$$

Where I_0= the measured output power,

Ii = the reference input power and

L = the length of the optic fiber

Optical input power is the power incides into the fiber from the optical source and the optical output

power is the power received at the fiber end.
The attenuation can be classified into two:
i. Intrinsic losses – losses caused by substances inherently present in the fiber like impurities and imperfections in the glass. An example of an intrinsic loss is material absorption and Rayleigh scattering.
ii. Extrinsic losses- losses or attenuation caused by external forces such as macro bending.

The loss mechanisms contributing to attenuation in an optical fiber are; absorption, Scattering due to inhomogenities in the core refractive index (Rayleigh scattering), Scattering due to irregularities at the boundary between core and cladding, Bending loss (macro and micro bending), Loss at joints and connectors, and Coupling losses at the input or output and mode coupling and leaky modes losses.

Bending Loss

Bending loss in the form of macro and micro bending is another loss mechanism that contributes to loss as light propagates along the fiber.
Micro bend loss is due to microscopic fiber deformations in the core-cladding interface and is usually caused by poor cable design and fabrication. Non- uniform lateral stresses during the cabling and the deployment of the fiber in the ground introduces micro bends [15].
Macro bends are bends on a fiber having a large radius of curvature (bend)/ diameter relative to the fiber core diameter that is *r>>a* where *a*, denotes the core radius, and *r* the radius of curvature [15, 9]. Macro bend losses are usually encountered during the in-house and installation process of the optic fiber.

Macrobends can be characterized by a bend angle, bend diameter or a bend radius also known as radius of curvature. When a fiber is bent the incident angle is compromised and total internal reflection fails and thus the light is no longer confined and guided by the core of the fiber.

Mathematical modeling of light ray in Step index fiber

Consider an interface between two optically different media of refractive indices n_1 and n_2 . When a ray is incides . When a ray is incident at the interface both refraction and reflection take place. If θ_i is the angle of incident of the ray then according to Snell's law:

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_2}{n_1} \qquad (6)$$

Where θ_r is the angle of refraction of a ray.
If a ray travels from a high refractive index medium (n_1) to a low refractive index medium (n_2) it bends away from the normal.
For a single-mode step index fiber with length *l*, bending loss (*L*) is usually obtained by [16]

$$L = 10\log 10(\exp(2\alpha l)) = 8.686\alpha l, \qquad (7)$$

Where α is the macro bending loss coefficient, and it is a function of bending radius, wavelength of ray used in the fiber, and also optical fiber structure and material of the fiber. Often when macro bending reaches a critical radius of curvature (R_c), then loss due to bending can be neglected, and R_c is defined as [17]

$$R_c = \frac{3n_2\lambda}{4\pi(NA)^3} \qquad (8)$$

Where R_c is the critical radius of bending, n_2 is the refractive index of the clad, *NA* is the numerical aperture of the fiber and λ is the wavelength.
Easily the macro bended fiber is modeled as a curved dielectric slab surrounded by an infinite cladding, then by this approach a closed form of solution might be obtained.

Although the simple torodial coordinate system is of relevance in realistic situation, unfortunately no exact solution of Maxwell's equations exists in this frame. So different approaches have been employed for evaluation of the macro bending loss. Macro bending loss coefficient *(2α) (dB/km*) which has been proposed by Marcuse, according to the mode coupling theory is presented as eq. (3) [18]

$$2\alpha = \sqrt{\pi}\delta^2 L_c\left(\frac{2n_1Ka\Delta}{bW}\right) - \sum_s exp\left\{-\left[\left(\beta_g - \beta_{1s}\right)\frac{L_c}{2}\right]^2\right\}\frac{J_1^2\left(j_{1s}\frac{a}{b}\right)}{J_0\left(j_{0s}\right)} exp\left(\frac{-2a^2}{W^2}\right) \qquad (9)$$

which usually is considered in step index optical fibers, uses Bessel function of zero and first order (J_0, J_1) and also the root of Bessel function (J_{0s}, J_{1s}), with boundary conditions $J_0(J_{0s}) = 0$, $J_1(J_{1s}) = 0$. Tsao and Cheng have modified *eq.(9)* for 2α, and they considered other parameters like number of wrapping turns(N), and curve fitting function (F), and also V number, and the suggested formula is as follows:

$$2\alpha = 2FN\left[4\sqrt{\pi}\delta^2\frac{1}{\Lambda_c}\left(\frac{n_1 k\Delta}{b}\right)^2 - \sum_s J_1^2\left(J_{1s}\frac{b}{a}\right)V^{-2}\right] \qquad (10)$$

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

$$\Lambda_c=2R \qquad (11)$$

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

$$L_R = \eta_{R1}\, exp\,(-\eta_{R2} \cdot R) \qquad (12)$$

Where η_{R1}, η_{R2} are fitting parameters, and for $\lambda = 1550\ nm$, their values are given as *70* and *0.5* respectively. Although their results show good agreement with this model, in their work, fluctuation behaviour of loss against radius was not considered. Also they did not mention whether η_{R1}, η_{R2} are functions of bending radius or wavelength only. They also proposed a linear relationship between losses and number of turns as in eq.(13).

$$L_N = \eta_N N \qquad (13)$$

Where L_N is the loss due to the number of wrapping turns (N), η_N is constant, which has 0.01 value and N is number of turns.

In most of these models one can see the effect of refractive index of the fiber (core and clad) and their differences (Δ), which are important physical parameters.
It is claimed [19], that oscillation of macro bending loss appears for sufficiently strong curvature, i.e., when R is smaller than the threshold value of bending radius (R_{th}) which is given by

$$R_{th} = 2k^2 n_2^2 \frac{b}{\gamma^2} \qquad (14)$$

Where $k = 2\pi/\lambda$, n_2 is the refractive index of the clad, $\gamma = [\beta_0^2 - k^2 n_2^2]^{1/2}$, where β_0 is the complex propagation constant and $b = (x^2 + y^2)^{1/2}$.

To get the loss using the given value of bending radius and wrapping turn those are shown in Table 1 and Table 2 respectively. Using equation (12) and equation *(13)*, the Tables and the below graphs generated by Mathematica 5.1 Software.

Table 1 correspondence data of bending radius with loss

Bending Radius(mm)	Loss(dB/mm)
4.0	9.47347
4.5	7.37795
5.0	5.74595
5.5	4.47495
6.0	3.48509
6.5	2.71419
7.0	2.11382
7.5	1.64624
8.0	1.28209
8.5	0.9985
9.0	0.77763
9.5	0.60562
10.0	0.47166
10.5	0.36733
11.0	0.28607
11.5	0.22279
12.0	0.17351
12.5	0.13513
13.0	0.10524
13.5	0.08196
14.0	0.06383
14.5	0.04971
15.0	0.03872

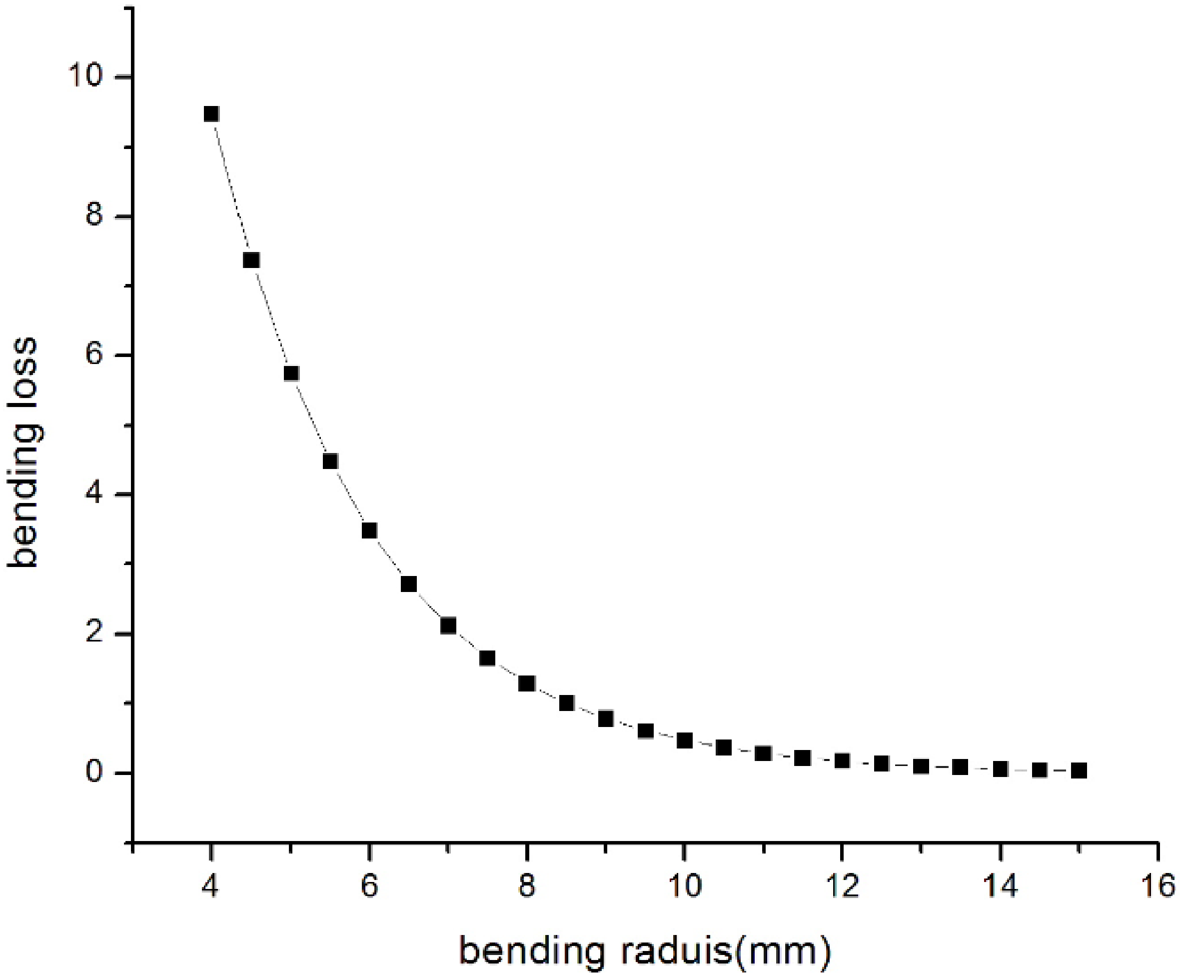

Fig. 3 bending radius vs. bending loss

Figure 1 shows that the bending loss depend on the bending radius of the step index fiber which has the core and cladding refractive indices are $n_1 = 1.48$ and $n_2 = 1.46$ respectively. Light wave, 1550nm wave length transmitted to the optical fiber; have different bending radius as shown in the figure 1. As the bending radius increases by 0.5mm the bending loss also varies relating with it. The variation seams like exponentially varying graph.

Table 2 a corresponds data of number of turn with loss

Number of turns(N)	Loss(dB/unit)
1	0.01
3	0.03
5	0.05
7	0.07
9	0.09
11	0.11
13	0.13
15	0.15
17	0.17
19	0.19
21	0.21
23	0.23
25	0.25
27	0.27
29	0.29
31	0.31

33	0.33
35	0.35
37	0.37
39	0.39
41	0.41
43	0.43
45	0.45
47	0.47
49	0.49
51	0.51

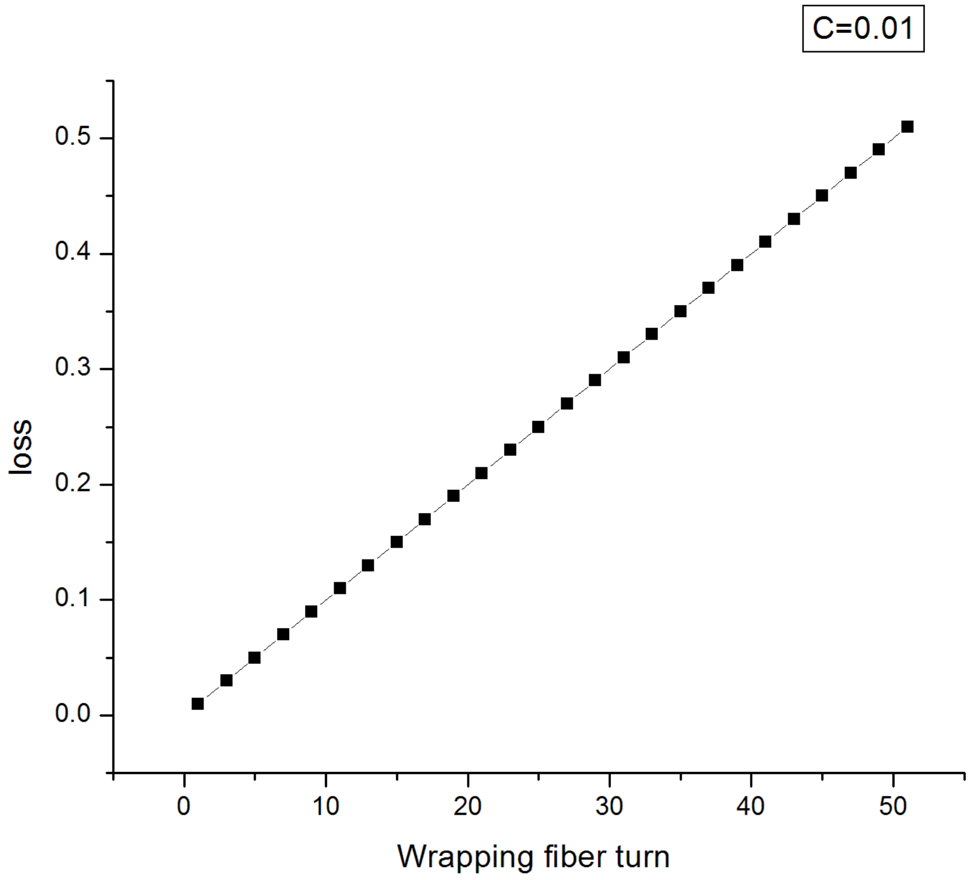

Fig. 4 loss as a function of wrapping turns for step index single mode fiber

Figure 2 shows that the loss depends on wrapping turn of the step index single mode fiber which has different wrapping turn with 1 step size give varies loss values. When the wrapping turn increases, the loss increases directly. There is a direct linear relationship between the loss and wrapping turn flowing through the single mode step index fiber for the varying intensity values.

V. Conclusions

In this research, investigation of how the loss of intensity of light energy in step index fiber depends on bending radius and wrapping turn which varies from *4mm-15mm* and *1-51* turns respectively at a given refractive index $n_1 = 1.48$ and $n_2 = 1.46$
The paper found that the loss in step index fiber increases as the bending radius and wrapping turn increases

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