The effect of macro-bending on power confinement factor in single mode fibers

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Abstract. One of the methods to determine the macro-bending effect in a single mode fiber is by calculating its power loss coefficient. We describe an alternative method by using the equation of fractional power in the fiber core. Knowing the fiber parameters such as its core radius, refractive indexes, and operating wavelength; we can calculate the \( V \)-number and the fractional power in the core. Because the value of the fiber refractive indexes and the propagation constant are affected by bending, we can calculate the value of the fractional power in the core as a function of the bending radius. We calculate the fractional power in the core of an SMF28 and SM600 fiber and, to verify our calculation, we measure its transmission loss using an optical spectrum analyzer. Our calculations and experimental results showed that for SMF28 fiber, there is about 4% power loss due to bending at 633 nm, about 8% at 1310 nm, about 20% at 1550 nm, and about 60% at 1064 nm. For SM600 fiber, there is about 6% power loss due to bending at 633 nm, about 11% at 850 nm, and this fiber is not suitable for operating wavelength beyond 1000 nm.

1. Introduction
Macro-bending loss in optical fibers has been realized since in the early years of its application in communication systems. Many researchers have investigated this phenomenon theoretically and experimentally. Gambling et al., for example, explained that when light propagates from a straight fiber to a curved section the field distribution changed considerably so that in addition to a pure bending loss there is also a transition loss due to mode conversion in the transition region [1]. Modeling of bend losses for a realistic single mode fiber with multiple cladding layers has been presented by Wang et al. [2] and Zendehnam et al. [3]. They showed that light reflection at the interface between the cladding layer and the coating layer of the fiber has an apparent effect so that the bend loss value of a standard single mode fiber was not a monotonic function of the bending radius but oscillating with both wavelength and bending radius.

Power loss occurred in a bent optical fiber was not desired in the application in communication systems. However, in contrast with the application in communication systems, bending loss phenomena could be useful for optical fibers intended as sensors. By tailoring the refractive index profile of the fiber, a bend-sensitive fiber can be produced with bending loss five times more than that of the ordinary G.652A single mode fiber [4]. One of the methods to calculate bending loss in an ordinary single mode fiber is by calculating its power loss coefficient, for example by using a classical formula introduced by Marcuse [5]. In this paper, we describe an alternative method to determine the
macro-bending effect by using the equation of fractional power propagating in the fiber core. Knowing the fiber parameters such as its core radius, the refractive index of the cladding, numerical aperture, and operating wavelength we can calculate the $V$-number, the normalized propagation constant, and the fractional power propagating in the core for the $LP_{01}$ and $LP_{11}$ modes. Because the value of the fiber refractive indexes and the normalized propagation constant are affected by bending, we can calculate the value of the fractional power propagating in the core as a function of the bending radius. As a case study, we calculate the optical power loss of an SMF28 and SM600 fiber. To verify our analysis, we measure its transmission spectra using an optical spectrum analyzer. This method could be useful to determine the combination of the wavelength of the light source with an ordinary single mode fiber (not a bend-sensitive fiber) that will be used as an intensity-based sensor based on macro-bending effect.

2. Methods
Most practical telecommunication-grade single mode fibers are classified as weakly guiding because the difference in refractive index of the core and the cladding is very small, less than 0.01 [6, 7]. Under this condition, the modes propagate in the fiber are assumed to be nearly transverse with an arbitrary set of polarization, called as Linearly Polarized ($LP$) modes. The equation for studying these modes is simply written as [7]

$$U \left( J_{m+1}(U) \right) = W \left( \frac{K_{m+1}(W)}{K_m(W)} \right)$$  \hspace{1cm} (1)

where $U$ and $W$ are fiber parameters that can be expressed in terms of the normalized propagation constant $b$ and the normalized frequency $V$ of the fiber, so that

$$W = \sqrt{b} \text{ and } U = \sqrt{1 - b}$$  \hspace{1cm} (2)

Using equation 2 in equation 1 we obtained that for $m = 0$ (fundamental mode)

$$V(1 - b)^{1/2} \left[ J_1(1 - b)^{1/2} \right] = Vb^{1/2} K_1 \left[ b^{1/2} \right]$$  \hspace{1cm} (3)

and for $m \geq 1$ (higher order modes)

$$V(1 - b)^{1/2} \left[ J_{m+1}(1 - b)^{1/2} \right] = -Vb^{1/2} K_{m-1} \left[ b^{1/2} \right]$$  \hspace{1cm} (4)

For a given value of $m$, there will be a finite number of solutions and the $n^{th}$ solution ($n = 1, 2, 3, ...$) is referred as the $LP_{nm}$ mode. The modal power carried in the core, as well as in the cladding, of a single mode optical fiber is one of the important parameters of the fiber. The fractional power propagating in the core is mathematically written as [7]

$$\eta = \frac{P_{core}}{P_{total}} = \left[ \frac{W^2}{V^2} + \frac{U^2}{V^2} \left( \frac{K_m(W)}{K_{m+1}(W)} \right) \right]$$  \hspace{1cm} (5)

The normalized propagation constant $b$ is directly related to the effective refractive index ($n_{eff}$)

$$b = \frac{n_{eff}^2 - n_{clad}^2}{NA^2}$$  \hspace{1cm} (6)

where $NA$ is the numerical aperture of the fiber
and the normalized frequency \((V)\) of the fiber is
\[
V = \frac{2\pi}{\lambda} \cdot a \cdot NA
\]  
(8)
where \(a\) is the fiber core radius and \(\lambda\) is the operating wavelength.

When the fiber is circularly bent with a bending radius of \(R\), the refractive index of the fiber is changed due to stress-optic effects [8]
\[
n'_{\text{clad}} = n_{\text{clad}} \left(1 + \frac{a}{R_{\text{eff}}} \right) \quad \text{and} \quad n'_{\text{core}} = n_{\text{core}} \left(1 + \frac{a}{R_{\text{eff}}} \right)
\]  
(9)
where \(R_{\text{eff}}\) is the effective bend radius due to the stress-optic effects, for silica (SiO_2) fiber \(R_{\text{eff}} = 1.28R\) [8], \(n_{\text{clad}}\) and \(n_{\text{core}}\) is, respectively, cladding and core refractive index of the unbent fiber. To determine the value of the refractive index at a different value of wavelength, we use the Sellmeier equation for SiO_2 as the cladding material [9]. The normalized propagation constant of the bent fiber \((b_{\text{bent}})\) is therefore [8]
\[
b_{\text{bent}} = \frac{n'_{\text{eff}} - (n'_{\text{clad}})^2}{(n'_{\text{core}})^2 - (n'_{\text{clad}})^2}
\]  
(10)
Using this normalized propagation constant value into equation 2, the fractional power in the core of the bent fiber, \(\eta_{\text{bent}}\), can be calculated using equation 5.

To verify our analysis, we then measure the transmission spectra of the fiber by using an optical spectrum analyzer (ANDO AQ-6312B). The measurement range is from 600 to 1600 nm with 10 nm resolution. The fiber samples are a two meters patchcord of SMF28 and SM600 from Thorlabs Inc. Firstly, we record the transmission of white light when the fiber patchcord is in a straight condition, and when it is circularly bent with a certain radius. As a white light source, we use a stabilized Xenon lamp (Thorlabs SLS201). To bend the fiber patchcord we use a concentric cylinder made from acrylic with varied diameter from 50 mm to 10 mm in 5 mm step. The block diagram of our measurement is shown in figure 1.

![Block diagram of the transmission measurement.](image)

3. Results and discussion
The graph of the fractional power in the core \((P_{\text{core}}/P_{\text{total}})\), calculated from equation 5, as a function of inverse bending radius \((1/R, \text{in } \text{cm}^{-1})\) for an SMF28 fiber \((a = 3.9 \mu \text{m}, NA = 0.12)\) is shown in figure 2.
For light with 633 nm wavelength, the value of the \(V\)-number of this fiber is 4.65 with unbent propagation constant \(b = 0.82\). This means the fiber is multi-moded in this wavelength and not sensitive to bending. As shown in the graph, when the fiber is straight (bending radius \(R = \infty\) or \(1/R = 0\)) the fractional power in the core of the \(LP_{01}\) mode is 0.96 and decreases slightly to 0.92 when the bending radius is 0.5 cm (\(1/R = 2\) cm\(^{-1}\)), indicating 4% or 0.18 dB loss of power [10]. At 1310 nm, the fiber is single-moded because the \(V\)-number is 2.24 with unbent propagation constant \(b = 0.47\). At this wavelength, the power loss is 8% or 0.36 dB because the fractional power in the core of the \(LP_{01}\) mode for a straight fiber is 0.79 and decreases to 0.69 when the bending radius is 0.5 cm. At 1550 nm the fiber is more sensitive to bending than that at 1310 nm, because at this wavelength the unbent propagation constant \(b = 0.36\) and the \(V\)-number is 1.9. The fractional power in the core of the \(LP_{01}\) mode for a straight fiber is 0.70 and decreases to 0.56 when the bending radius is 0.5 cm, indicating power loss of 20% or 0.97 dB. This SMF28 fiber is very sensitive to bending at 1064 nm wavelength. At this wavelength, the \(V\)-number is 2.76; this means that this fiber is few-moded with the unbent propagation constant for \(LP_{11}\) mode of \(0.18\). The fractional power in the core of the \(LP_{11}\) mode for a straight fiber is 0.64 and decreases to 0.24 when the bending radius is 0.5 cm so that the power loss at this wavelength is 60% or 3.98 dB.

![Figure 2](image-url)  
**Figure 2.** Fractional power in the core as a function of inverse bending radius for SMF28 fiber.

The graph of the fractional power in the core as a function of inverse bending radius for an SM600 fiber \((a = 1.3 \mu m, NA = 0.14)\) is shown in figure 3. This fiber is single-moded at 633 nm with the \(V\)-number = 1.81 and the unbent propagation constant \(b = 0.33\). When the fiber is straight, the fractional power in the core of the \(LP_{01}\) mode is 0.67 and decreases a little to 0.63 when the bending radius is 0.5 cm (6% or 0.27 dB power losses). Clearly, this fiber is not so sensitive to bending at this wavelength. At 850 nm, this fiber is single-moded with the \(V\)-number = 1.35 and the unbent propagation constant \(b = 0.17\). The fractional power in the core of the \(LP_{01}\) mode for a straight fiber is 0.44 and decreases to 0.39 when the bending radius is 0.5 cm (power loss of 11% or 0.5 dB). At this wavelength, the fiber could be sensitive to bending if the bending radius is less than 0.5 cm. At 1310 nm, our calculation showed that the fractional power in the core of the \(LP_{01}\) mode for a straight fiber is 0.15 and decreases to 0.07 when the bending radius is 1.4 cm (53% or 3.31 dB power losses). This fiber, however, cannot be used at this wavelength since the \(V\)-number is 0.88 with propagation constant \(b = 0.04\).
Figure 3. Fractional power in the core as a function of inverse bending radius for SM600 fiber.

The result of our measurements on transmission spectra of the SMF28 and SM600 patchcords at different bending radius is shown in figure 4. The setting of the optical spectrum analyzer was as follows: Start wavelength = 600 nm, Stop wavelength = 1600 nm, Resolution = 10 nm. For the SMF28 patchcord, the top trace is a straight fiber and then, respectively, for bending radius $R$ of 1.5, 1, and 0.5 cm (lower trace). As can be seen, the fiber is sensitive to bending in the 1020 - 1120 nm wavelength range as well as in 700 – 720 nm range. There are about 3.5 dB losses when the fiber is bent with bending radius 0.5 cm at 1064 nm, while the bending loss at 633 nm, 1310 nm, and 1550 nm is negligible. For the SM600 patchcord, the top trace is a straight fiber and then for $R$ of 1, 0.50, and 0.25 cm (lower trace), respectively. It can be seen that this fiber is not sensitive to bending at 633 nm; there is about 0.5 dB loss when the fiber is bent with bending radius 0.5 cm at 850 nm (and about 3 dB loss when the fiber is bent with bending radius 0.25 cm but not recommended in practice because it can damage the fiber), and no transmission at all beyond 1000 nm. Overall, the measurement results matched with the power confinement factor analysis.

Figure 4. Transmission spectra of the SMF28 (left) and SM600 (right) patchcords at different bending radius.

A : straight
B : bending radius 1.5 cm
C : bending radius 1 cm
D : bending radius 0.5 cm

A : straight
B : bending radius 1 cm
C : bending radius 0.5 cm
D : bending radius 0.25 cm
4. Conclusions
The fractional power in the core \( \left( \frac{P_{\text{core}}}{P_{\text{total}}} \right) \) of a single mode optical fiber is one of the important parameters of the fiber. Since its value is affected by macro-bending, we can determine the bending characteristics for a certain fiber at a particular wavelength. This calculation does not take into account the presence of the fiber coating. The fiber is modeled as a core surrounded by virtually infinity cladding and the Fresnell reflection at the interface between cladding and coating is neglected. This calculation, however, could be used as a quick tool to determine the combination of the operational wavelength of the light source with an ordinary single mode fiber (not a bend-sensitive fiber) that will be used as an intensity-based sensor based on macro-bending effect. Our calculations and experimental results showed that, if the fiber is bent with a bending radius of 0.5 cm, about 3.5 dB losses occurred at 1064 nm for SMF28 fiber, and about 0.5 dB loss occurred at 850 nm for the SM600 fiber.

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