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Macro-Bending Loss of Single-Mode Fiber beyond Its Operating Wavelength

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Abstract

A standard telecommunication-grade single-mode optical fiber is designed to have a low macro-bending loss in its entire operating wavelengths to comply with the ITU-T Recommendation G.652. In this paper, we described the potential use of such a fiber as an intensity-based sensor due to the macro-bending loss as an alternative to using a bending-sensitive fiber. We calculated the macro-bending loss of several single-mode optical fiber patchcords using the classical Marcuse equation at several wavelengths, and measured its transmission loss due to bending using an optical spectrum analyzer. For each type of fibers there is a wavelength with a significant macro-bending loss of the LP_{11} *mode when the V-number of the fiber lies between 2.4 and 4, and that of the* LP_{01} *mode when the V-number of the fiber lies between 1 and 2.4. This work shows a thorough mathematical and experimental analysis for the posibility in using standard telecommunication fibers for intensity based-fiber sensor taking the benefit of bending loss phenomenon using commercial light sources.*

Keywords: *macro-bending loss, single-mode fiber patchcord, intensity-based sensor, Marcuse equation, v-number*

1. Introduction

Most standard telecommunication-grade single-mode optical fibers, for example, the SMF28™ fiber [1], is classified as a step-index weakly-guiding fiber by making the core thin and the refractive index different between the core and cladding small [2]. The modes that propagate in such a fiber are weakly guided, but the guidance is still good when the fiber is bent with radii of tens of centimeters [2]. Loss of power due to macro-bending is not desired in optical fiber communication systems which commonly operating in 1300 – 1600 nm range of wavelengths. According to the ITU-T Recommendation G.652, the maximum macro-bending loss at 1550 nm for 100 turns of fiber with 37.5 mm bending radius is 0.50 dB [3]. Certainly, this type of fiber is not suitable as an intensity-based sensor which utilizing the bending loss phenomena in optical fiber so that a specially designed fiber, namely the bend-sensitive fiber, should be used [4]. Nevertheless, as an alternative to using the bend-sensitive fiber, this weakly guiding fiber is potential to be used as an intensity-based sensor because, at a certain wavelength, either the LP_{01} mode or the LP_{11} mode is sensitive to bending and has a significant optical power loss.

Theories of bending loss in optical fiber have been reported by numerous of researchers. In 1975 Marcuse derived a loss formula for optical fibers with a constant radius of curvature [5]. In 1978 Murakami and Tsuchiya derived bending loss formula for coated fibers [6]. A simple approach to calculating bending loss of coated single-mode fibers was introduced by Renner in 1992 [7]. In 2007 Schermer and Cole improved the simplified formula introduced by Marcuse [8], and in 2013 Schulze *et al* used that formula to calculate the macro-bending loss of an SMF28™ fiber at 1064 nm [9]. Most of the authors, except Schulze *et al*, discussed bending loss of the single-mode fiber at a wavelength of 1300 nm and 1500 nm since it is the popular wavelength used in optical communication systems.

A wide range of research on optical fiber sensors based on bending loss phenomena in an optical fiber has also been reported. For example, Wang *et al* developed a voltage sensor

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based on macro-bending structure [10]. A liquid level sensor based on macro-bending coupling is reported by Zhang *et al* [11]. The use of an intensity-based sensor to monitor differential settlement of the earth-rock junction is reported by Qiu *et al* [12]. A patent about a method for measuring the deformation of a specimen using a fiber optic extensometer is filed by Gupta *et al* [13]. Again most of the authors discussed bending loss at wavelength of 1300 - 1500 nm. Previously, we have reported the use of a telecommunication-grade single-mode fiber as an optical extensometer at 1310 nm and 1550 nm [14], and at 1050 nm [15], but without a detail mathematical explanation.

In this paper, we report a thorough mathematical and experimental analysis for the posibility in using standard telecommunication fibers for intensity based-fiber sensor taking the benefit of bending loss phenomenon using commercial light sources available in the market. We calculated the macro-bending loss at a certain wavelength by using the modified Marcuse's formula for several types of fibers, namely the SM600™, 780HP™, and SMF28™ fiber from Thorlabs, Inc. The SM600™ is an optical fiber designed to operate in 633 – 780 nm; while the operating wavelength of the 780HP™ and SMF28™ fiber is 780 – 970 nm and 1260 – 1625 nm, respectively [1]. Our analysis based on the fact that below the cut-off wavelength, the fiber is not single moded and the high order mode is prone to bending; while above cut-off the fundamental mode is not confined well in the fiber core and is also prone to bending [16]. To support our analysis we also measured the transmission loss due to bending for each fiber by using an optical spectrum analyzer.

2. Theory

The simplified bend loss formula for a circularly-bent optical fiber with core radius *a*, modified by taking into account the mechanical stress through the use of the effective bend radius (R_{eff}) is given by [8, 9]:

$$2\alpha = \frac{\pi^{1/2}\kappa^{1/2} exp\left(-\frac{2\gamma^3 R_{eff}}{3\beta_Z^2}\right)}{e_m R_{eff}^{1/2}\gamma^{3/2}V^2 K_{m-1}(\gamma a)K_{m+1}(\gamma a)} \tag{1}$$

here 2α is the power loss coefficient, $R_{eff} = 1.2R$ to $1.4R$ (R is the nominal or experimental bend radius), κ and γ are the field decay rates in the core and cladding, V is the normalized frequency of the fiber, β_z is the propagation constant of the guided mode in the unbent fiber, $K_{m\pm1}$ is the modified Bessel function of the second kind, and e_m is a scalar depending on the order of the mode LP_{mn} ($e_m = 2$ for $m = 0$, and $e_m = 1$ for $m \neq 0$)

$$\kappa = \sqrt{k^2 n_1^2 - \beta_z^2} \tag{2}$$

$$\gamma = \sqrt{\beta_z^2 - k^2 n_2^2} \tag{3}$$

$$V = \frac{2\pi}{\lambda} a\sqrt{n_1^2 - n_2^2} \tag{4}$$

where n_1 and n_2 are the refractive index of the core and cladding, respectively, $k = (2\pi/\lambda)$ is the wave number and λ is the wavelength.

To calculate the propagation constant β_z, at first we must determine the value of the normalized propagation constant *b* and then use the relationship [16]:

$$b = \frac{\left({}^{\beta_Z}/_{k}\right)^2 - n_2^2}{n_1^2 - n_2^2} \tag{5}$$

The value of *b* can be determined graphically from the normalized *b* – *V* curve for several LP modes of a step index fiber, for example from the graph on page 2254 in Reference 2 or from a similar graph on page 153 in Reference 16. For LP_{01} mode the value of *b* can be easily calculated as [2]:

$$b = 1 - \left(\frac{1+\sqrt{2}}{1+(4+V^4)^{1/4}}\right)^2 \tag{6}$$

The SI unit of the power loss coefficient *2α* in Eq. (1) is m^{-1}. Usually, the bending loss is expressed in dB/m and it can be obtained by multiplying *2α* by the factor 4.343 (or *10×log e*) [8]. To calculate the bending loss at a certain wavelength, we must determine the value of the fiber refractive indexes (n_1 and n_2) at that particular wavelength. The cladding material of most telecommunication-grade optical fibers is glass/pure silica (SiO_2) [16], and the value of its refractive index as a function of wavelength λ (in μm) is determined by Sellmeier equation [17]. Sellmeier proposed the dispersion formula for optical application which gives refractive index as a function of wavelength and it is expressed as follows [17]:

$$n_2^2 = 1 + \frac{A_1\lambda^2}{\lambda^2-\lambda_1^2} + \frac{A_2\lambda^2}{\lambda^2-\lambda_2^2} + \frac{A_3\lambda^2}{\lambda^2-\lambda_3^2} \tag{7}$$

The constants for SiO_2 are, respectively, $A_1 = 0.696749$, $A_2 = 0.408218$, $A_3 = 0.890815$, $\lambda_1 = 0.069066$ *μm*, $\lambda_2 = 0.115662$ *μm*, *and* $\lambda_3 = 9.900559$ *μm* [17]. Using this equation, the refractive index of the cladding (n_2) at a certain wavelength can be determined. For example, at λ = 1.55 μm, the value of n_2 is 1.4444. Finally, the refractive index of the core can then be determined by the numerical aperture (*NA*) of the fiber, since

$$NA = \sqrt{n_1^2 - n_2^2} \tag{8}$$

This simplified bend loss formula does not take into account the presence of the coating. The fiber is modeled as a core surrounded by a virtually infinity cladding. The Fresnel reflection at the interface between cladding and coating, the source of an oscillatory behavior of the bend loss as a function of the bending radius, is neglected [9].

3. Research Method

As described before, the analyzed single-mode optical fibers are the SM600™, 780HP™, and SMF28™. To calculate the macro-bending loss for each fiber using Eq. (1) we made a simple program using Matlab™. Inputs for the program were the wavelength (λ), fiber core radius (*a*) and its numerical aperture (*NA*), and the bending radius (*R*). We then calculated the value of refractive indexes (n_1 and n_2), R_{eff}, the *V*-number, propagation constant (β_z), *et cetera* to obtain the value of *2α* at a particular value of λ and *R*. The flowchart of our programming calculation is presented in Figure 1. Fiber parameters as the input for our calculation are given in Table 1.

Table 1. Fiber Parameters

Fiber Type	Core Diameter (μm)	Numerical Aperture
SMF28™	8.2	0.117
SM600™	4	0.14
780HP™	2.6	0.14

We then measured the transmission for each fiber by using an optical spectrum analyzer ANDO AQ-6312B. The measurement range was from 600 to 1600 nm with 10 nm resolution. The fiber samples were a two meters patchcord of SMF28™, 780HP™, and SM600™ from Thorlabs Inc. Firstly, we recorded the transmission of white light when the fiber patchcord was in a straight condition, and then when it was circularly bent with a certain radius. As a white light source, we used a stabilized Xenon lamp Thorlabs SLS201. To bend the fiber patchcord, we used 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 2.

4. Results and Analysis

The graph of the calculated bending loss in dB/m as a function of bending radius in cm for SMF28™ fiber at wavelength 1320 nm and 1550 nm is presented in Figure 3. It can be seen that our result is similar to the work of Schermer and Cole [8] although the method to calculate the propagation constant β_z is different. This indicates that we can apply our program to calculate the bending loss for other wavelengths or another type of fibers.

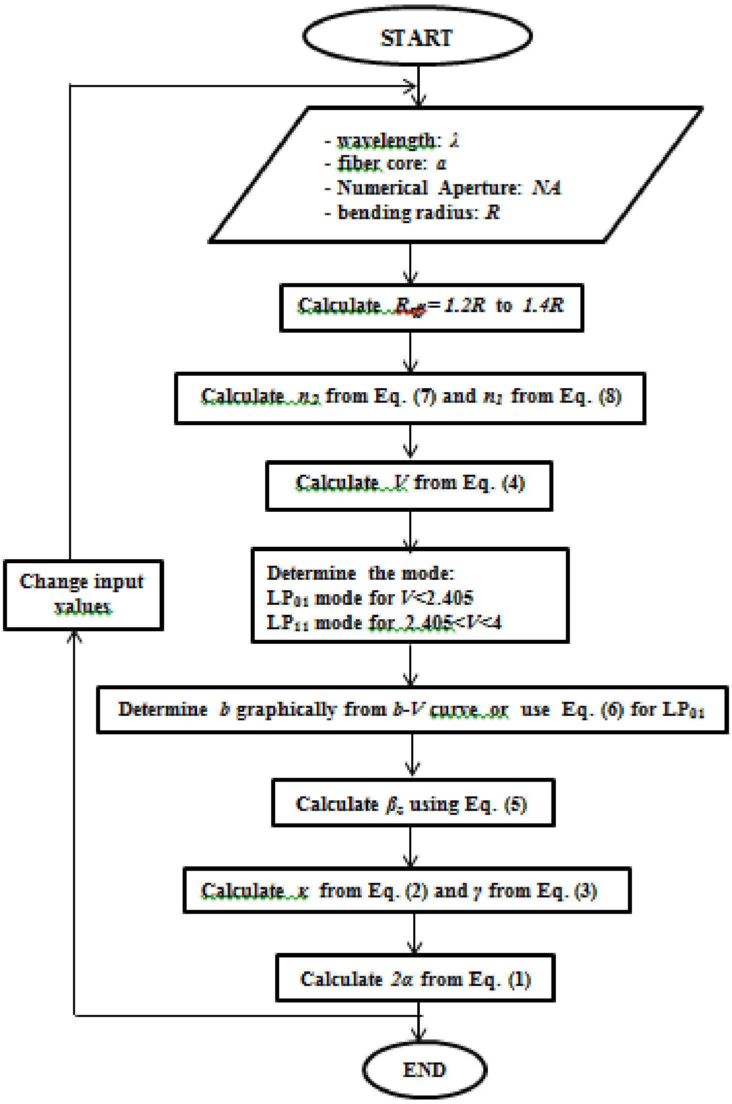

Figure 1. The flowchart for the bending loss calculation

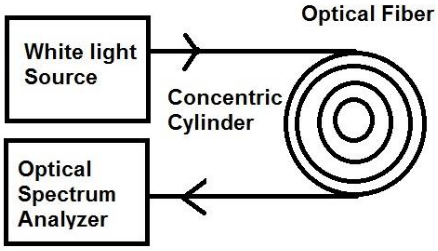

Figure 2. Block diagram of the transmission measurement system

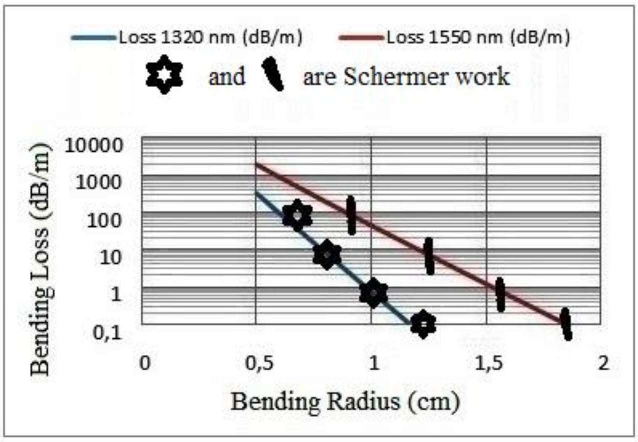

Figure 3. Calculated bending loss (in dB/m) for SMF28™compared to Schermer work

In practice, losses are simply expressed in dB so that we will present the graph of the calculated bending loss for each fiber in dB as a function of the bending radius in cm. The value of bending loss in dB is obtained by multiplying its value in dB/m with the bending length, L_{bent}, which is equal to the circumference of the wrapped fiber, in this case, $L_{bent} = 2\pi R$. For practical purpose, the displayed value for the minimum and the maximum loss is 0.1 dB and 10 dB, respectively; and, to enhance the difference, the scale of the bending radius is same from 0.5 cm to 3 cm for each fiber.

Figure 4 shows the calculated bending loss for the SMF28™ fiber. As expected, the bending loss is small at 1320 nm (the *V*- number of the fiber is 2.3) and slightly increased at 1550 nm (*V*=1.9). This is because the SMF28™ fiber is designed as a telecommunication-grade fiber in this wavelength range. The loss is 0.1 dB when this fiber is bent with a radius less than 1 cm (for 1320 nm) and about 1.5 cm (for 1550 nm). However, at 1064 nm (*V*= 2.8) the bending loss is significant. At this wavelength, the fiber already suffered 0.2 dB loss by a mere 2.5 cm bending radius and increased to about 3 dB when the bending radius is 1.5 cm.

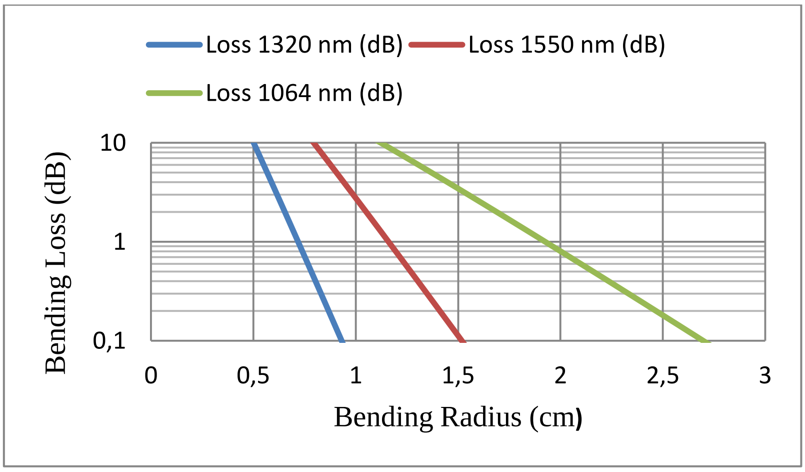

Figure 4. Calculated bending loss (in dB) for SMF28™ fiber

Figure 5 shows the calculated bending loss for the SM600™ fiber which is designed to operate at 633-780 nm. To have a 0.2 dB loss this fiber must be bent with a bending radius of 1 cm (at 780 nm, *V*=1.5), 1.5 cm (at 850 nm, *V*=1.3), and 2.3 cm (at 915 nm, *V*=1.2). At 915 nm the loss is increased to 4 dB when the bending radius is 1.5 cm.

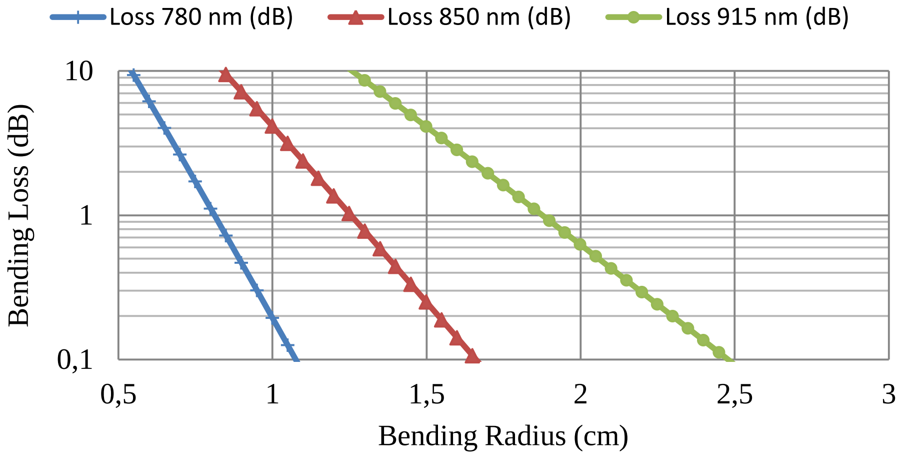

Figure 5. Calculated bending loss (in dB) for SM600™ fiber

Figure 6 shows the calculated bending loss graph for the HP780™ fiber which operates at wavelengths 780-970 nm. As can be seen this fiber has a low bending loss at 980 nm (*V*= 1.8) and 1064 nm (*V*=1.7), but at 1310 nm (*V*=1.3 nm) the bending loss is significant, i.e. 0.2 dB at a bending radius of 2.3 cm increased to 5 dB at a bending radius of 1.5 cm.

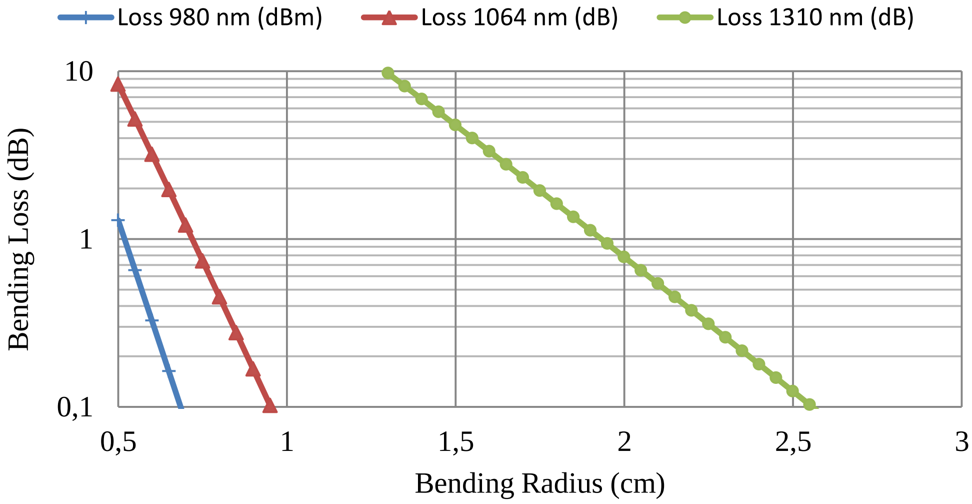

Figure 6. Calculated bending loss (in dB) for 780HP™ fiber

To support our calculation, we measured the transmission for each fiber by using an optical spectrum analyzer. The typical results are presented in Figures 7 to 9 for SMF28™, SM600™ and 780HP™ fibers respectively. It can be seen that the SMF28™ fiber is sensitive to bending at the wavelengths of 970, 980, 1050 and 1064 nm (see Figure 7), the SM600™ fiber is sensitive to bending at the wavelength of 850 nm and 915 nm (see Figure 8), while the 780HP™ fiber is sensitive to bending at wavelengths of 1300 – 1350 nm (see Figure 9).

In Table 2, we resume the results of the analytical and experimental results which reveal some usable wavelengths for each of the tested fiber patchcord which can be used for sensing purpose based on the macro-bending loss phenomenon. For example, we can use the combination of an SMF28 fiber with a 1050 or 1064 nm light source.

The resulted of usable wavelengths for bending loss utilization here covered a wider range of wavelength from 970 to 1350 nm compared to those from most of the earlier authors discussed bending loss sensors using single mode fiber at standard telecommunication wavelength of 1300 nm and 1500 nm [10-13].

Table 2. The Usable Wavelength for Bending Loss Utilization

Fiber Type	Operating Wavelength (nm)	Usable Wavelength (nm)
SMF28™	1260 - 1625	970, 980, 1050, 1064
SM600™	633 - 780	850, 915
780HP™	780 - 970	1300-1350

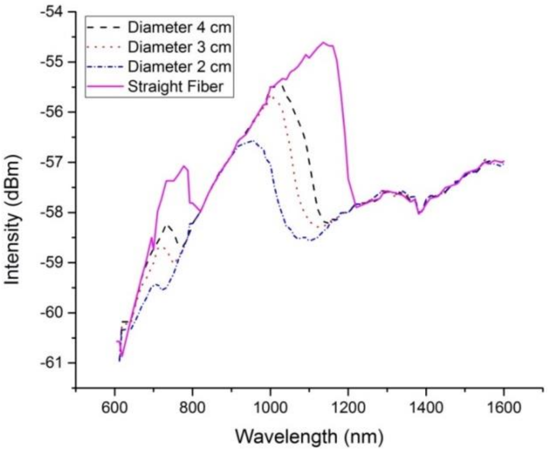

Figure 7. Transmission curve for the SMF28™ fiber patchcords

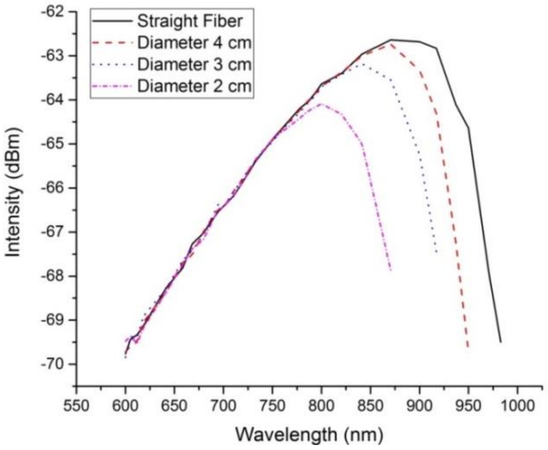

Figure 8. Transmission curve for the SM600™ fiber patchcords

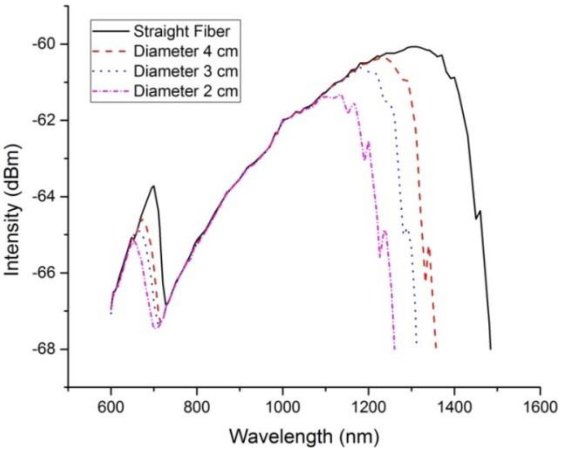

Figure 9. Transmission curve for the 780HP™ fiber patchcords

The bending loss calculated using the simplified Marcuse formula is bigger than the measurement result. The worst is for the SMF28 with 1 cm bending radius, the bending loss value at 1064 nm is about 13 dB (calculated, see Figure 4) and 3 dB (measured, see Figure 7). This is because the fiber is modeled as a simple structure that consists of a core with the radius *a* surrounded by a cladding with an infinite radius, while the fiber being measured is in the form of a patchcord that has several layers of material for mechanical protection. This formula, however, is a quick tool to analyze the tendency of bending loss of a step-index single-mode fiber based on its basic parameters without the need to know the parameters of the coating and protecting material.

5. Conclusion

We have demonstrated, analytically and experimentally, that although single-mode optical fibers have a small bending loss in its operating wavelength however, at a certain wavelength, the bending loss value is considerable. For each type of fibers there is a wavelength with a significant macro-bending loss of the LP_{11} mode when the V-number of the fiber lies between 2.4 and 4, and that of the LP_{01} mode when the V-number of the fiber lies between 1 and 2.4. This means that we can use every type of single-mode optical fiber as an intensity-based sensor, by utilizing its bending loss property, provided that the wavelength of the light source is matched with the bending characteristics of the fiber.

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