Comparison of Different Deformation Functions Modeling Micro-bending Loss of Optical Fibers on Sandpaper Test

Zoltán Várallyay(1*), Tamás Mihálffy(1), Kazunori Mukasa(2)
(1)Furukawa Electric Institute of Technology, H-1158 Budapest, Késmárk u. 28/A, Hungary
(2)Furukawa Electric Co., Ltd., 20-16 Nobono, Kameyama, Mie, 519-0292, Japan
*zoltan.varallyay@furukawaelectric.com

Abstract: Different deformation functions to find the best fit to the experimental data of micro-bending loss measurements of optical fibers are investigated. Best outcome, fitting the parameters is in the form of a Gaussian power spectrum. © 2022 The Author(s)

1. Introduction

Increasing density of optical fibers in optical fiber cables is highly demanding and 6912 fiber cables with cable diameters of just 29 mm has been already made commercially available [1]. Reduction of fiber diameter is an effective way to increase the density of optical fiber cables, but this makes them exposed to micro-deformations and increases the micro-bending loss to a greater extent. The simulation of micro-bending loss is essential to optimize thin diameter fibers, but this requires complex computations because one has to take not only (i) the optical effects (mode distributions) but also (ii) the mechanical properties of the glass and the coatings into account. As for the optical simulation, the coupled mode theory (CMT) [2], evaluating the coupling of the propagating core modes to radiation cladding modes due to micro-deformations of the fiber glass, has been investigated. On the other hand, despite the importance of the mechanical investigations that provide the shape of the deformations for micro-bending loss evaluation, only few investigations have been reported so far [3], [4].

For separate deformations where the extent of the distortion is smaller than their average separation, Olshanski came up with a correlation function using an exponential form with a problem specific adjustable parameter [5]. This kind of correlation function to calculate micro-bending loss is used recently to evaluate the loss properties of trench-guided optical fibers [6] having more complicated structures than simple step-index profiles.

In this conference paper, we investigate 42 different fibers, that are different in index profiles as well as glass and coating designs to give a new unique insight in the mechanical and optical simulations. We derive new power spectrum functions, we fit the unknown parameters to the measurements, and we compare the results and adjustable parameters.

2. Theory

Micro-bending loss according to CMT is calculated by the multiplication of the coupling coefficient C_{1s}^2 between the LP_{01} core and LP_{1s} type radiation modes and the power spectrum of the deformation function $\Phi(\Delta\beta_{1s})$ [2]:

$$2\alpha_m = \sum_{s=1}^{\infty} C_{1s}^2\, \Phi(\Delta\beta_{1s}) \tag{1}$$

where $\Delta\beta_{1s} = \beta_{01} - \beta_{1s}$ is the propagation constant difference of the LP_{01} core mode and the LP_{1s} radiation mode where $s = 1,2,\dots,\infty$ and where we can do the summation for a finite number of radiation modes due to the nature of $\Phi(\Delta\beta_{1s})$ that is a decaying function resulting in negligible small contribution from large s values. To evaluate the coupling coefficient, one needs a mode solver to obtain the electric field distributions of the necessary modes, and the coupling coefficient can be evaluated thus in the following way

$$C_{1s}^2 = \frac{k^2}{2}\frac{\left(\int_0^\infty \frac{\partial n_0}{\partial r} E_{01}E_{1s}\, rdr\right)^2}{\int_0^\infty E_{01}^2 rdr \int_0^\infty E_{1s}^2 rdr} \tag{2}$$

where E_{01} is the electric field distribution of LP_{01} and E_{1s} is the field distribution of LP_{1s} modes, k is the wavenumber and n_0 is the initial refractive index profile of the fiber without any deformation. The normalized power spectrum of the $f(z)$ deformation distribution is given by

$$\Phi(\Delta\beta_{1s}) = \frac{1}{2L}\left|\int_{-L}^{L} f(z)\exp(-i\Delta\beta_{1s}z)dz\right|^2 \tag{3}$$

where L is the length of the deformation centered around zero and z is the axial coordinate. Choosing deformation function that has a power spectrum in the form of $1/\Delta\beta_{1s}^{2p}$ was introduced by Olshanski [5] in connection with that $p\cong 1.1$ was obtained for measurement of coiled fibers on a fiber drum [3]. That is a question what value we can get for p in the sandpaper test with higher surface roughness than that in [3]. We discuss this at the end of the Section Results.

Other shape of the normalized power spectrum of the deformation function at the spatial frequency $\Delta\beta_{1s}$ can be found if we investigate the mechanical deformation of the fiber on sandpaper particles. In the followings we compare our micro-bending measurements to the calculations using different shape of the power spectrum of the deformations, and we fit the p exponential factor to the experiments. We also introduce based on the mechanical computations new type of $\Phi(\Delta\beta_{1s})$ formula and compare the results to the above-described approximation.

3. Results

We use sandpaper with an average particle size of 18.3 μm ± 1 μm and the particles are 32 μm far from each other to cover the surface of a 280 mm diameter fiber drum and we coil the fiber on it. A few hundred meters of fiber is used, and the transmission loss (α_{sp}) is measured from 1100 nm to 1650 nm. We remove the fiber from the sandpaper surface to ensure a stress-free state of the fiber under test and the transmission loss (α_{sf}) is measured again. The difference of the two measurements provides the value of micro-bending loss: $\alpha_m=\alpha_{sp}-\alpha_{sf}$ where indices 'sp' and 'sf' are referring to 'sandpaper' and 'stress-free', respectively. We use several drawn fiber samples from 65 μm glass diameter to 125 μm glass diameter with different refractive index profiles and different primary and secondary coating thicknesses.

We have analyzed the optical fiber as it is deformed by a particle using finite element analysis. The model contains a piece of fiber segment, and its end facets are disabled to move in the *z* and *y* directions, only up and down (*x*-direction, See Fig. 1). One end of the fiber is touching the particle and the other end is loaded by a force that has a magnitude comparable to the tension used during fiber coiling in the experiments. The obtained displacement function with a fiber length of 1 mm is shown in Fig. 1 that displacement of the core resembles to a Gaussian profile. If we assume that the deformation function has a Gaussian shape, we can write that function in the following form

$$f(z) = Ae^{-\frac{z^2}{2b^2}} \tag{4}$$

where A and b are positive, real numbers. Similarly, a deformation function in the form of $A \cdot z \cdot e^{-z^2/(2b^2)}$ can be defined but as we show below this does not add to the accuracy of micro-bending loss modeling related to sandpaper test. Using Eq. (3), one can calculate the power spectrum of the deformation given by Eq. (4) obtaining the following form

$$\Phi(\Delta\beta_{1s}) = (Ab)^2 e^{-b^2\Delta\beta_{1s}^2} \tag{5}$$

where A is practically the amplitude of the deformation which depends on the diameter of the fiber glass and the thickness of the coatings. Therefore, one can write the micro-bending loss in the following form using Eq. (1), (5) and the assumption for the amplitude (A) suggested in Ref. [7] (secondary coating has small contribution, omitted now):

$$2\alpha_m = \overbrace{a^2 \cdot e^{-\frac{2d_g}{\tau_g}} e^{-\frac{2t_p}{\tau_p}}}^{\text{Mechanical effect}} \cdot \underbrace{b^2 \sum_{s=1}^{N} C_{1s}^2 \cdot e^{-b^2\Delta\beta_{1s}^2}}_{\text{Optical effect}} \tag{6}$$

where d_g is the diameter of the fiber glass, t_p is the thickness of the primary coating and a, τ_g and τ_p are parameters characteristic to the experiment. The first three terms are related to the magnitude of the deformation, namely the mechanical effects while the summation is related to the mode overlap and the propagation constant difference, thus the optical properties.

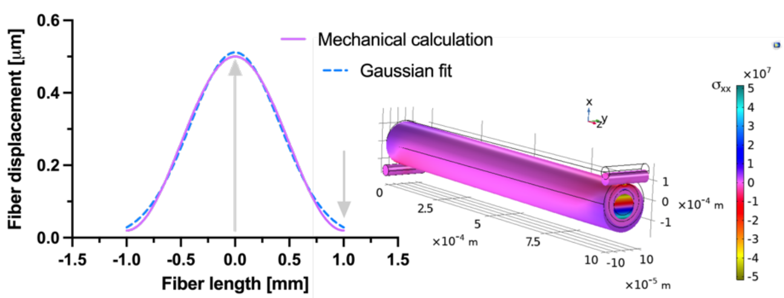

Fig. 1. The model to calculate the mechanical deformation of a piece of fiber including primary and secondary coatings, and the obtained displacement function along with a fitted Gaussian profile.

Mechanical simulation considers the stiffness of the glass and the coatings, and a 125 μm standard glass diameter and standard coating thicknesses with 250 μm outer diameter is used. The obtained magnitude in Fig. 1 with sub-micrometer amplitude of the deformation is in good agreement with a recent experiment to determine the shape and magnitude of micro-deformations using a multi-core fiber [4].

We use the expression obtained in Eq. (6) to compute the micro-bending loss for each experimentally investigated optical fiber designs applying three different deformation functions: $1/\Delta\beta_{1s}^{2p}$ that is the functional form introduced by

Olshanski [5] with p=0,1,2, and $e^{-b^2\Delta\beta_{1s}^{2p}}$ that is obtained in Eq. (5) assuming the Gaussian deformation of the fiber and an additional exponential factor p similar to Olshanski's formula. As it is shown in Table 1, we have also calculated with $\Delta\beta_{1s}^{2p}e^{-b^2\Delta\beta_{1s}^{2p}}$ power spectrum function but this did not improve the micro-bending model giving the same regression parameter as for the Gaussian deformation.

The loss calculation is inserted in a constrained optimization algorithm with minimum and maximum boundaries and changed the parameters until the best fit is obtained to the experimental results. The two different power spectra of the deformations yield different simulation results as shown in Fig. 2 and the fitted lines have different slope on the graph. The correlation between the two different calculation methods and the measurements are good for both models but slightly better for the Gaussian approximation obtained in Eq. (5). R^2 regression parameter is 0.934 for the first case and 0.951 for the Gaussian form as shown in Table 1 and 0.95 for the more complicated, combined Gaussian and power formula. The p parameter in the $1/\Delta\beta_{1s}^{2p}$ formula is obtained to be 2.2387 for the sandpaper test that is close to 2 as mentioned in Ref. [5] and as a contrast to 1.1 in Ref. [3] where the surface roughness was less than in our experiments with the fibers coiled on sandpaper.

Table 1. Different deformation functions, power spectrum of the deformations, obtained parameters and the accuracy of the regression (R^2). A amplitude parameter contains a, τ_g, τ_p as it is written in Eq. (4), (5) and (6).

$f(z)$	$\Phi(\Delta\beta_{1s})$	a	τ_g	τ_p	b	p	R^2
$A \cdot \lvert z \rvert$	$A\,\Delta\beta_{1s}^{-2p}$	10^5	12.8	9.8	–	2.2387	0.934
$A \cdot e^{-z^2/(2b^2)}$	$A^2b^2e^{-b^2\Delta\beta_{1s}^{2p}}$	10^3	25.4	19.5	3.02	0.2582	0.951
$A \cdot z \cdot e^{-z^2/(2b^2)}$	$A^2 \cdot b^6 \cdot \Delta\beta_{1s}^2 \cdot e^{-b^2\Delta\beta_{1s}^{2p}}$	$10^5/6$	25.4	19.5	4.04	0.2043	0.950

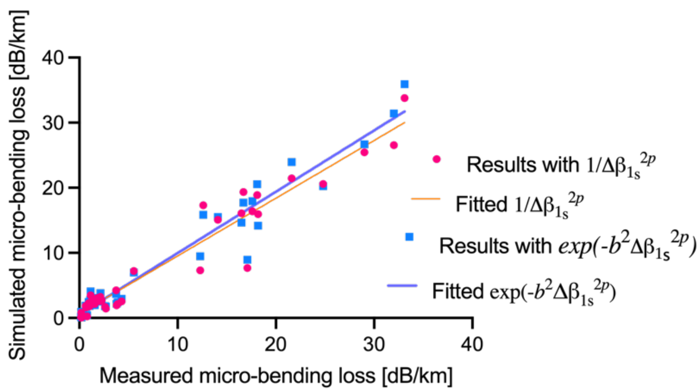

Fig. 2. The measured and simulated micro-bending loss using two different power spectrum functions at 1550 nm.

4. Conclusion

We have derived the loss formula for micro-bending loss in case of two different Gaussian deformations caused by sandpaper particles including the important mechanical properties of the fiber glass and coatings. We compared the experimental and simulation results using three different power spectrum functions after optimization of the simulation parameters in the loss formula given in Eq. (6). We obtained better agreement with the experiments using the Gaussian form for the deformation function. For the p parameter we have obtained a value of 2.2387 in case of sandpaper on the drum in the $1/\Delta\beta_{1s}^{2p}$ power spectrum formula showing an increasing value of p with the surface roughness the fiber is tested on.

5. References

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