An Overview of Macrobending and Microbending of Optical Fibers

John A. Jay

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Introduction

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 1000 m of fiber. Today, Corning sells SMF-28® ULL optical fiber with the attenuation at 1550 nm specified to be ≤0.18 dB/km, a 100X improvement from the breakthrough results of 1970.

It is critical that the fibers' inherent low attenuation be preserved in service. Several extrinsic effects can increase the fiber attenuation. A critical effect is bending the fiber from a straight axis.

Bending can increase the attenuation of an optical fiber by two mechanisms: macrobending and microbending. Some bending is of course unavoidable, e.g., shipping and storage, optical cable manufacturing and installation as well as fiber termination and deployment. Understanding the fundamental nature of attenuation increase with bending enables development of products and usage conditions to maintain the initial superior attenuation of optical fiber.

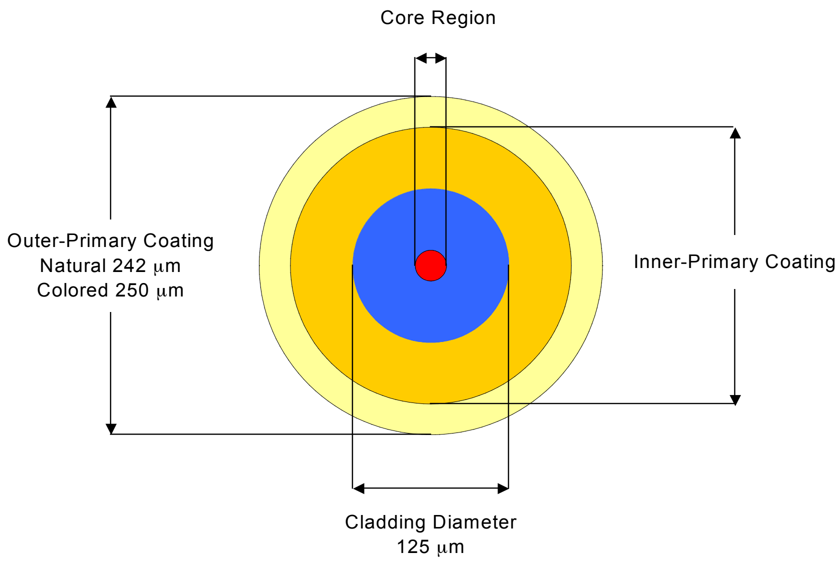
Properties of Optical Fiber

Today's common communications grade optical fiber designs (e.g., compliant with IEC 60793-2-10 and 60793-2-50 publications and the ITU-T Recommendations G.65x series) are based on a glass (i.e., "cladding") diameter of 125 μm. The region at the center of the fiber that carries the optical signal is called the "core", and can be anywhere from a few microns to 62.5 μm in diameter. The fiber properties that define its optical performance, i.e., the core, refractive index profile, etc., are often referred to as the "waveguide" – though it is also common to use the term to describe the whole fiber as well.

Typically a two layer UV curable acrylate coating system is applied on top of the glass, often referred to as the "primary" coating in anticipation of subsequent optical cable processing. The "outer-primary" layer on natural fiber is typically 242 – 245 μm outer diameter; a tertiary color layer is often applied that increases the diameter to ~250 μm – in some cases the color layer is contained in the original outer-primary layer. The "inner-primary" layer outer diameter can vary depending on manufacturer and product.

Figure 1 shows a communications grade optical fiber. For the reasons noted above, no dimensions are shown for the inner-primary diameter or the core region. Note that the use of a two layer system is optional (it is not required by industry standards) as are the coating materials, though UV curable acrylate materials are most common in the industry today.

Optical fiber cross section. The cladding (outer glass surface) and outer-primary coating diameters are specified in industry standards. The core diameter varies for different single-mode optical fibers, and is only specified for multimode fibers. The inner-primary coating diameter is not specified in industry standards.
Figure 1

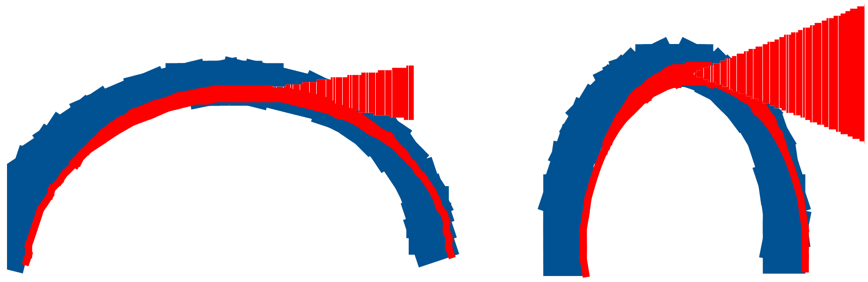


Macrobending

Macrobending Background

Macrobending of an optical fiber is the attenuation associated with bending or wrapping the fiber. Light can "leak out" of a fiber when the fiber is bent; as the bend becomes more acute, more light leaks out. This effect is shown schematically in Figure 2. In the figure on the left, a small percentage of the light is refracted out of the waveguide when it is bent. The figure on the right schematically illustrates that more light is shown refracted out of the fiber when it is bent to a smaller diameter.

Macrobending schematic diagram. When the fiber is bent from a straight deployment, some of the guided light is refracted out of the fiber. As the bend becomes more acute, more light is refracted out of the fiber.
Figure 2

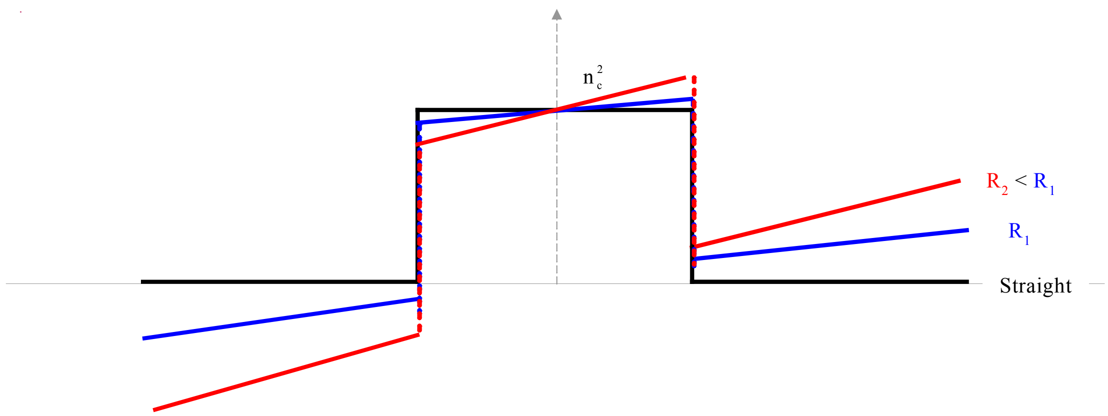


Macrobending is commonly modeled as a "tilt" in the refractive index profile based on the radius of curvature of the fiber bend[1]

(1) $$n_c^2(r,\theta) = n^2(r) + \frac{2n_1^2}{R} r \cos\theta$$

where $n_c^2(r,\theta)$ is a modified local refractive index dependent upon the fiber bend radius. Figure 3 plots the effect of different fiber bend radii on the effective refractive index profiles. The full analysis is beyond the scope of this paper, but the point from Figure 3 is that the effective index of refraction observed by the optical power changes with the bend radius, allowing signal power to leak out of the core, which increases the fiber attenuation.

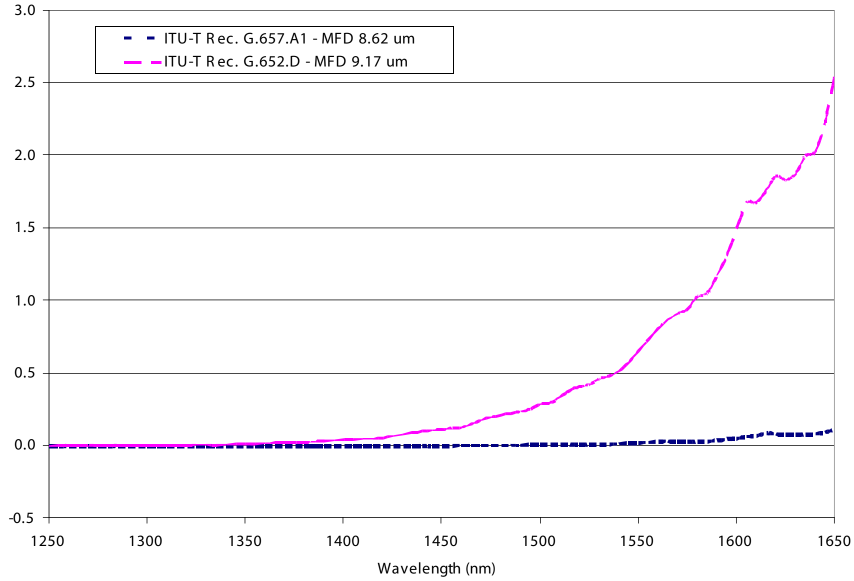
Effective refractive index profiles for a step index fiber bent to two different bend radii ($R_2 < R_1$). As the bend radius is reduced, the effective "tilt" in the refractive index profile increases.
Figure 3



For a given optical fiber, the attenuation increase depends on the radius of the bend, the number of bends (or length under bend) and the wavelength of the signal. The effect of wavelength is apparent in the pink curve in Figure 4. The lack of response at lower wavelengths until a threshold wavelength is reached and the exponential response at higher wavelengths are all characteristic of the common macrobending signature.

Effects of mode field diameter and wavelength on macrobending. The induced loss vs wavelength is shown for fibers compliant with ITU-T Recommendations G.652 Table D and G.657.A1 wrapped in a single 20 mm diameter bend. Below a threshold wavelength there is no attenuation increase. Above that threshold the attenuation increases rapidly with wavelength. There is a much reduced response for the fiber with the lower mode field diameter.

Figure 4

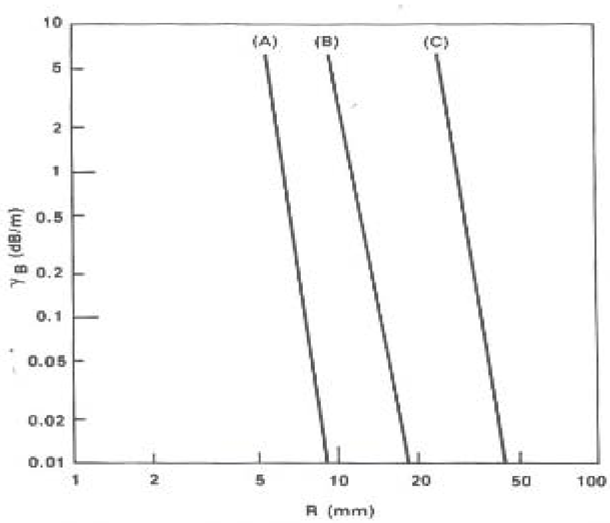


The effect of bend radius on macrobending is shown in Figure 5. Note how for each curve the attenuation increases logarithmically as the bend radius decreases.

Several properties of the fiber can be used to modify its sensitivity to macrobending. The most common is to change the refractive index profile. In general, increasing the refractive index difference between the core and cladding (the "delta") reduces a fiber's sensitivity to macrobending. In Figure 5 the attenuation increase at 1300 nm for three step index profile fibers are shown. The fibers have similar cutoff wavelength (λ_c), but different refractive index delta values as measured by numerical aperture (A = 0.253, B = 0.188, C = 0.108).

Macrobending attenuation at 1300 nm for fibers with different numerical apertures. The attenuation increases exponentially as bend radius decreases. In general, as the refractive index delta/numerical aperture increases, the fiber can be bent to a smaller radius for similar loss – results are a bit less clear in this figure as the waveguides were made to non-standard configurations to keep cutoff wavelength the same.[2]

Figure 5



Fiber Parameters & Attributes Affecting Macrobending

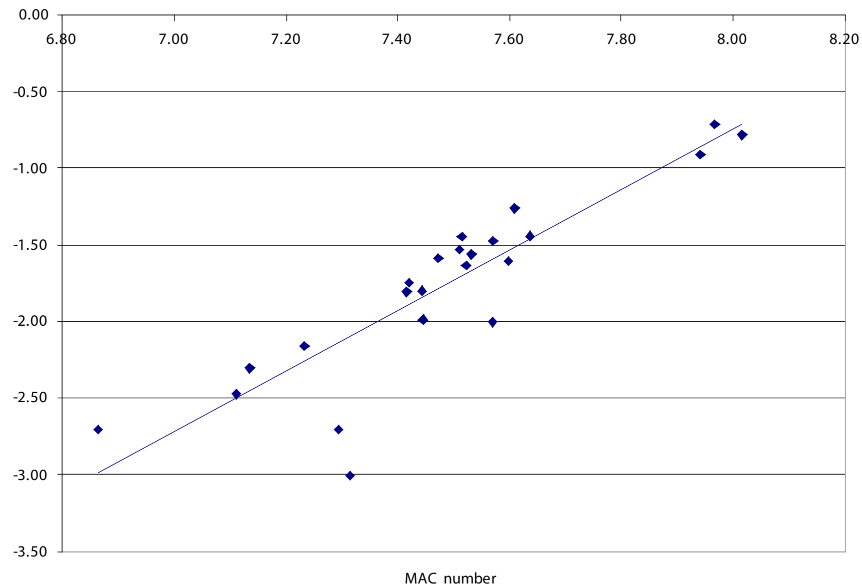
For single-mode fiber the most common refractive index profile change to combat bending losses is to reduce the mode field diameter. Figure 4 demonstrates this effect. The data on the blue curve comes from a sample with a lower mode field diameter than the sample used to create the data represented by the pink curve. Clearly the sample with larger mode field diameter is more sensitive to macrobending induced attenuation. Increasing the core-cladding refractive index difference and reducing the core diameter are two ways of designing a fiber with a smaller mode field diameter.

Fiber cutoff wavelength also affects macrobending performance, and the two attributes are commonly taken into [3] account simultaneously using an empirical parameter called the "MAC number". It is merely the ratio of the mode field diameter and cutoff wavelength in common units (e.g., micrometers).

In Figure 6 the relationship between MAC number and macrobending induced attenuation is shown. Like bend radius and attenuation, an exponential increase in attenuation is observed once a threshold value is reached. Figure 6 presents results for an ITU-T Recommendation G.652 compliant "step index" single-mode fiber ("standard fiber"). The relationship shown in Figure 6 may not apply to fibers with other refractive index profile designs.

Macrobending vs. the MAC number for an ITU-T Rec. G.652 Table D compliant fiber. The macrobending induced attenuation increases as the fiber MC number increases.

Figure 6



Macrobending in Industry Standards

Macrobending has been understood since the early days of fiber optics, and test methods and specifications have been in place since single-mode fiber was introduced commercially in the early 1980's.[4] Probably the first practical description for macrobending limits, and the first common industry specification, was introduced by Bell Communications Research ("Bellcore") in the mid-1980's. They developed a specification limiting the attenuation increase of 100 x 75 mm diameter turns to simulate the total number of fiber loops prepared when wrapping excess fiber lengths at all splice points in a common long haul link. Fiber cutoff wavelength also affects macrobending performance, and the two attributes are commonly taken into[3] account simultaneously using an empirical parameter called the "MAC number".

Today, an industry standard exists for measuring optical fiber macrobending, IEC 60793-1-47 *Measurement methods and test procedures – Macrobending loss*. The method basically consists of measuring the insertion loss of a fiber sample deployed in the specified bend radius. The standard describes the most common approach, wrapping the fiber on a mandrel of the specified diameter, as well as a "guiding groove on a flat surface", deploying the fiber in ¼-turn grooves machined into a flat surface. Another common technique is the "parallel plate" deployment in which the sample is "pinched" between two parallel, flat surfaces, and the test bend radius is determined by half the separation of the flat surfaces.

Industry standards containing macrobending specifications include IEC 60793-2-50 *Product specifications – Sectional specification for class B singlemode fibres*. Type 1.3 specifies the attenuation increase at 1625 nm for 100 turns of 30-mm radius to be less than or equal to 0.1 dB. ITU-T Recommendation G.652 Table D lists the same specification. The specified diameter was reduced from 75 mm to 60 mm in the early-1990s to reflect the use of smaller splice trays.

Some customized specifications from influential industry players still exist as well. For example, TPR 9430 *Verizon NEBS™ Compliance: Optical Fiber and Optical Fiber Cable* specifies the attenuation at 1550 nm is not to exceed 0.50 dB for 100 turns of 75-mm diameter (including intrinsic attenuation of the test of fiber) and not to exceed 0.50 dB for 1 turn of 32-mm diameter.

Practical Considerations of Macrobending

The Bellcore 75 mm specification[5] is an excellent example of mapping a practical use case to the product specification. More recently, as optical fiber is installed closer to the subscriber, it can be installed with even smaller bend radii. ITU-T Recommendation G.657 *Characteristics of a bending loss insensitive single mode optical fibre and cable for the access network* specifies several smaller bend radius deployments and sets fiber product specifications for each application.

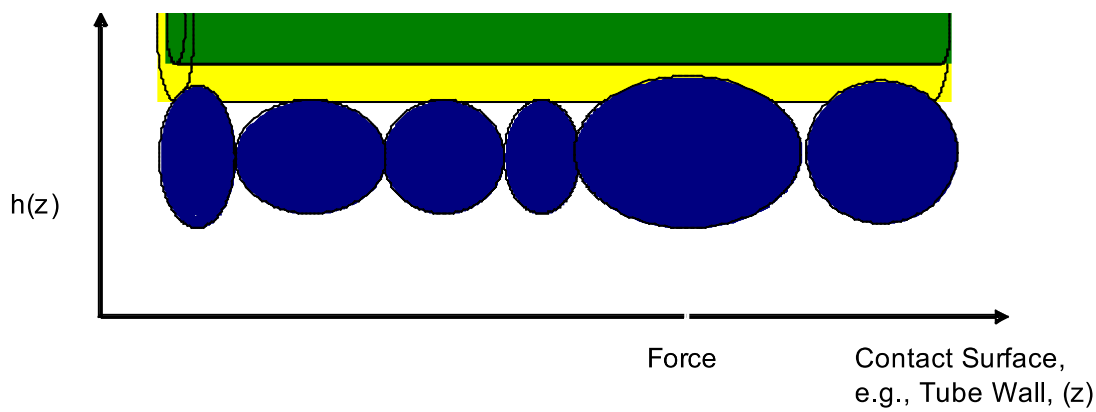
Microbending

Microbending Background

Microbending is an attenuation increase caused by high frequency longitudinal perturbations to the waveguide.[6] This is shown schematically in Figure 7. The perturbations are normally considered as a set of very small radius bends of the fiber core. The perturbations couple power among modes in the fiber, and in the case of single-mode fiber, couple power from the guided fundamental mode (LP_{01}) to higher-order modes from where the power dissipates through normal loss and scattering or refraction in to the acrylate coating.[7] The physical cause of the perturbations is usually assumed to be due to lateral contact of the fiber with surfaces in the optical cable or other deployment, as well as twists or other extrinsic stimuli.

Schematic representation of microbending. Physical irregularities on the surface in contact with the fiber perturb it into small radius bends which can cause microbending.

Figure 7

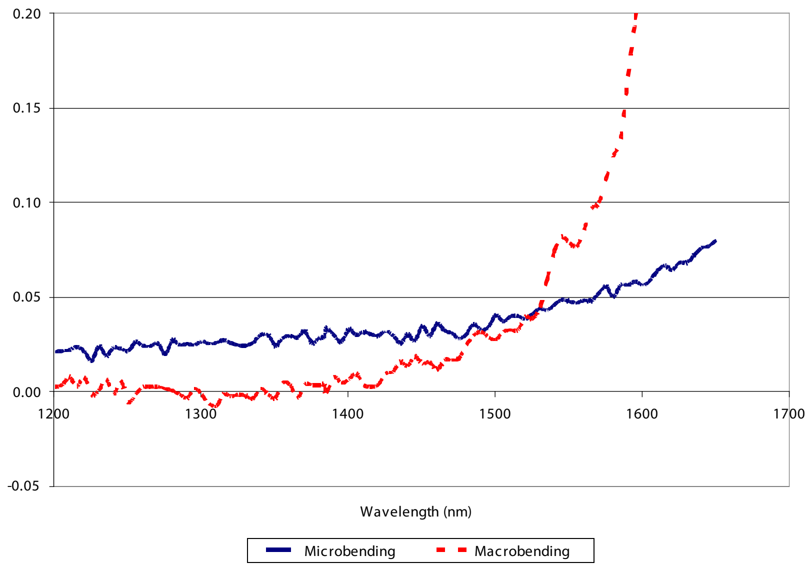


The small radius bends that cause microbending are typically <1 mm radius and are commonly described as a random variable with a distribution of spacing and amplitude. The parameters of the random variable power spectral density, along with the fiber geometry and waveguide design, can be used to predict the microbending attenuation increase for various loads.

A comparison of microbending and macrobending test results is shown in Figure 7. In this case, microbending is created by wrapping a fiber on a drum under tension on which the surface has been covered with a wire mesh. Example macrobending results for an ITU-T Recommendation G.652 Table D compliant fiber under 30 mm diameter bend are shown for comparison. The microbending results are similar to the macrobending results but show less wavelength dependency – the ratio of the increase at 1550 nm vs 1310 nm is lower than seen for macrobending. It is very difficult to remove any macrobending component from the response to a microbending stimulus, so there is often a wavelength dependency mixed in with microbending test results. Also, the core-cladding refractive index difference reduces with wavelength, increasing the microbending sensitivity, as shown in equation (3).

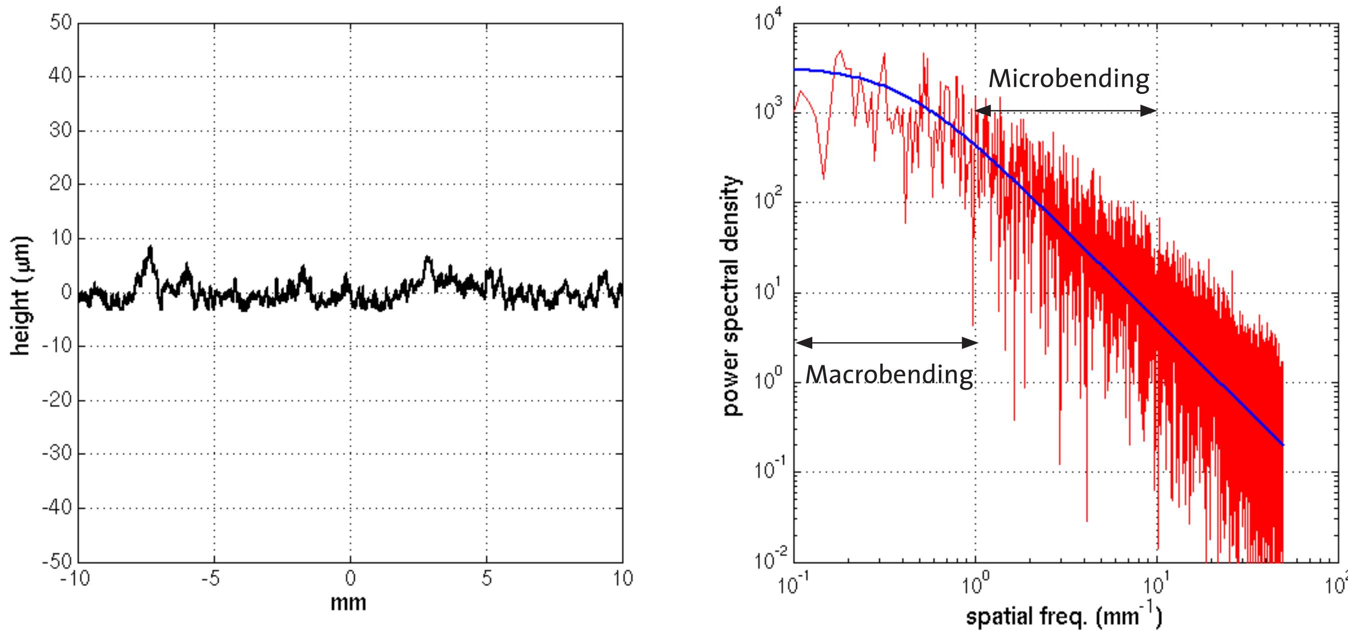
Example plots for macrobending and microbending for ITU-T Rec. G.652 compliant fibers. Note the macrobending results (30 mm diameter) resemble the macrobending "signature" seen in Figure 4: the attenuation does not increase until a "threshold" wavelength and then it increases rapidly. The microbending "signature" has much less wavelength dependency.

Figure 8



The key to this analysis – and to understanding the physical phenomenon of microbending – is to consider a fiber contact surface with a roughness that can be measured, i.e., the height of each perturbation measured along the length of contact. In the test procedure described above, imagine dragging a stylus along the wire mesh to measure the height of the wires along the length. A Fourier transform of the surface-height profile produces the spectrum of spatial periods presented as the power spectral density (PSD) of the surface. An example is shown in Figure 9. The left hand plot is the surface height profile, i.e., the measured distribution of size and space of the surface perturbations. The right hand plot is the PSD of the data in the left hand plot after Fourier transform.

The plot on the left is an example surface profile measurement. The plot on the right is a Fourier transform of the plot on the left, plotted as the power spectral density of those data. The perturbation frequencies associated with macrobending and microbending are superimposed on the plot on the right. The “threshold” between them is ~1 mm.
Figure 9



The difference between macrobending and microbending is superimposed on Figure 9. Long period perturbations (>1 mm) do not provide the right resonance to couple light to the cladding modes via microbending but can lead to macrobending. Short period perturbations (<200 µm) are spanned by the fiber and typically have little impact on attenuation. For most fiber profiles, the spatial periods of the rough surface between 0.2 and 1 mm are the most critical for microbending because they can provide the required interaction with the cladding modes and produce a significant deformation of the optical core.

This agrees with theory as well. Coupled mode theory explains that the correlation length to couple light between two modes should approximate the ratio of the wavelength to the difference of the refractive indices of the core and cladding. For example, in a single-mode fiber at 1550 nm,

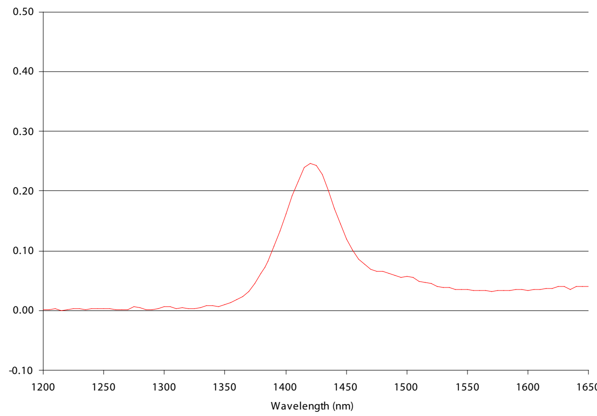
$$\Lambda = \frac{\lambda}{n_{core} - n_{cladding}} \qquad (2)$$

Λ = 1550 nm/(1.458 - 1.445) = 119 µm.

Details are beyond the scope of this paper but are described well in the literature.[9]

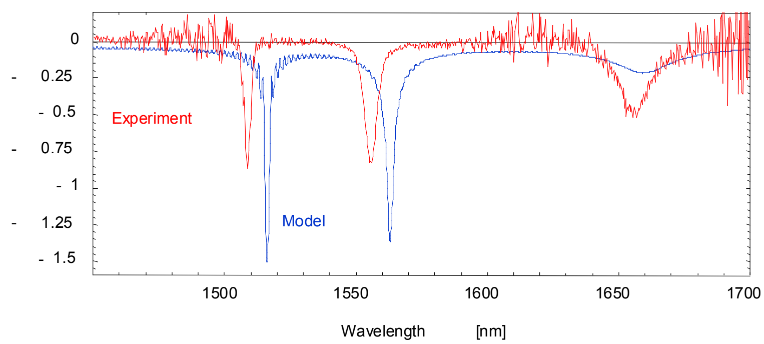
Conversely, if a controlled, periodic perturbation is applied to the fiber, microbending can act almost like a grating and remove power only at the wavelengths whose frequencies are associated with the period of the perturbation. Figure 10 shows an example of an experiment in which a fiber was subjected to a controlled, periodic perturbation. The perturbation was activated by winding the fiber at 70 g tension, causing the microbending attenuation spectrum shown in Figure 10. Unlike the example discussed above, however, a “narrow band” microbending signature is observed with only power between 1400 – 1450 nm effectively removed, corresponding with the period of the perturbation. The wavelength range of the narrow band response is determined by the spacing of the periodic perturbation.

Microbending attenuation increase for an experimental fiber subjected to a controlled periodic perturbation. The controlled perturbation limits the attenuation increase to a "narrow band" of wavelengths corresponding to the perturbation.
Figure 10



An additional example is shown in Figure 11. A controlled perturbation was applied to a test fiber by pressing it against a gear rack with known teeth spacing. This spacing corresponds to a narrow perturbation spectrum which would predict a very wavelength specific microbending response. The model and experimental results are shown in Figure 11. Indeed, the rack acts as a grating, "filtering" wavelengths corresponding to the teeth spacing.

Designed "narrow band" microbending prediction and experimental results. The predicted results for a perturbation corresponding to the spacing of the gear rack teeth are shown by the blue curve. Microbending data generated by pressing fiber against that same gear rack are shown by the red curve.
Figure 11



Fiber Parameters & Attributes Affecting Microbending

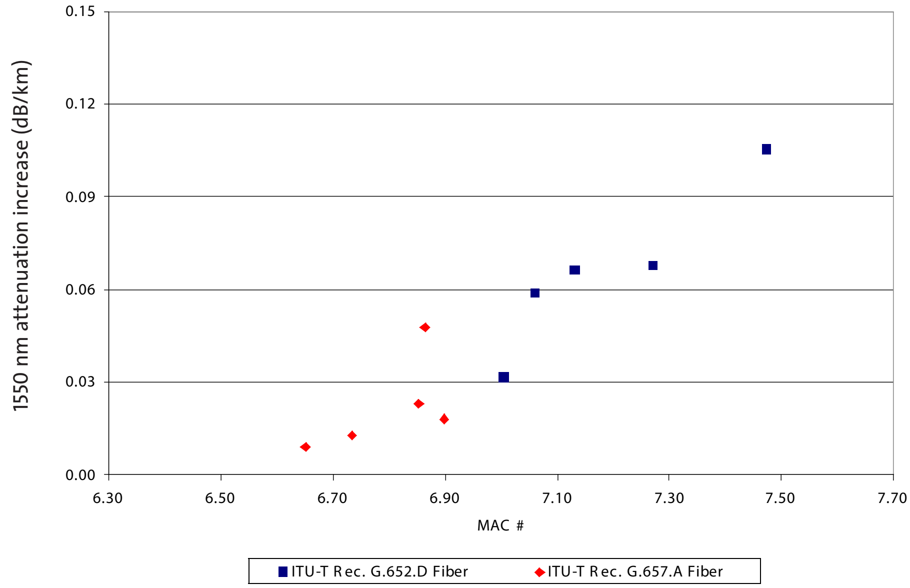
There are several design options to improve optical fiber resistance to microbending. They are shown in the following equation [10]

(3) $$\gamma = N < h^2 > \frac{a^4}{b^6 \Delta^3} \left(\frac{E}{E_f} \right)^{3/2}$$

where γ is the microbending induced attenuation increase, N is the number of bumps of average height h per unit length, b is the total fiber diameter, a is the core radius, Δ is the fiber refractive index difference and E_f and E are the elastic moduli of the fiber and the fiber surrounding material (i.e., coating) respectively.

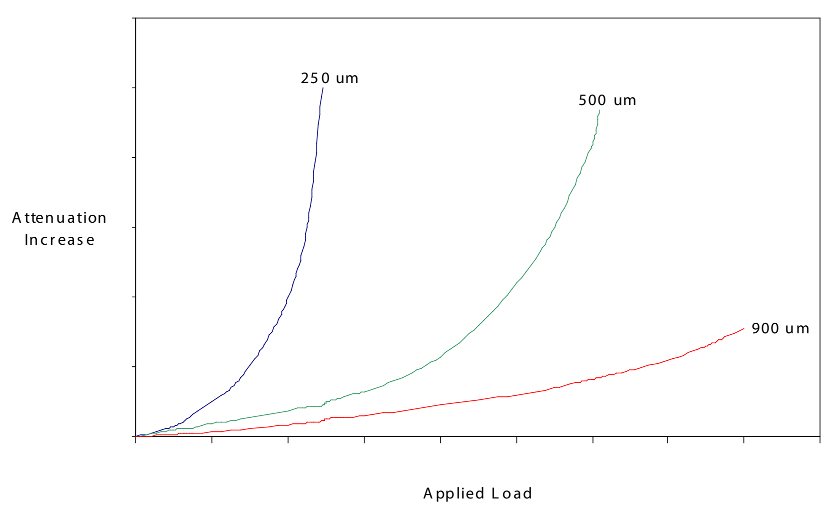
As equation (3) shows, the core radius and refractive index difference strongly affect the fiber microbending sensitivity. An example is shown in Figure 12. The blue squares present Wire Mesh Drum microbending test results for a commercially available single-mode fiber compliant with ITU-T Recommendation G.652 Table D. The red diamonds present results for an ITU-T Recommendation G.657.A1 compliant fiber. The refractive index profile design of this fiber is very similar to that of the blue-square fiber, except that the core radius is smaller and the refractive index difference larger. In fact, this design change was made to improve the macrobending performance (i.e., lower "MAC-value"), but microbending improved as well. This is seen clearly in Figure 12. This relationship has been noted empirically in the literature as well.[11]

Microbending results for ITU-T Recommendation G.652 and G.657 compliant fibers. Note the microbending induced attenuation reduces for smaller MAC number.
Figure 12



The fiber coating presents the next opportunity to design a product with improved microbending performance. From equation (3) the obvious approach is to increase the coating diameter thereby increasing the stiffness of the coated fiber. In fact large changes in coating diameter have a profound effect on microbending performance. The coating effectively functions as a low-pass filter of the external perturbations. Figure 13 presents results of microbend testing on single-mode fibers (125 µm glass diameter) with different coating diameters of 250 µm, 500 µm and 900 µm. As a load was applied to the fiber samples, the attenuation increased much more rapidly with load for the smaller coating diameters.

Microbending vs. coating diameter. Note the microbending sensitivity reduces as the coating diameter increases.
Figure 13



However there are again some limits to this approach placed by industry standards. IEC and ITU-T standards specify an uncabled coated fiber diameter of ~ 250 μm, and that is the common diameter of the products sold between optical fiber manufacturers and optical cable manufacturers. Small deviations around 250 μm generally do not affect the microbending sensitivity. It is common in the industry for an optical cable manufacturer to take a 250-μm diameter optical fiber and buffer it to 900 μm, typically by extruding a thermoplastic material over it. The directional microbending improvement seen in Figure 13 between 250 μm and 900 μm diameter products would be expected in this case. A 500-μm coated diameter is not a common industry standard for telecommunications grade optical fibers today.

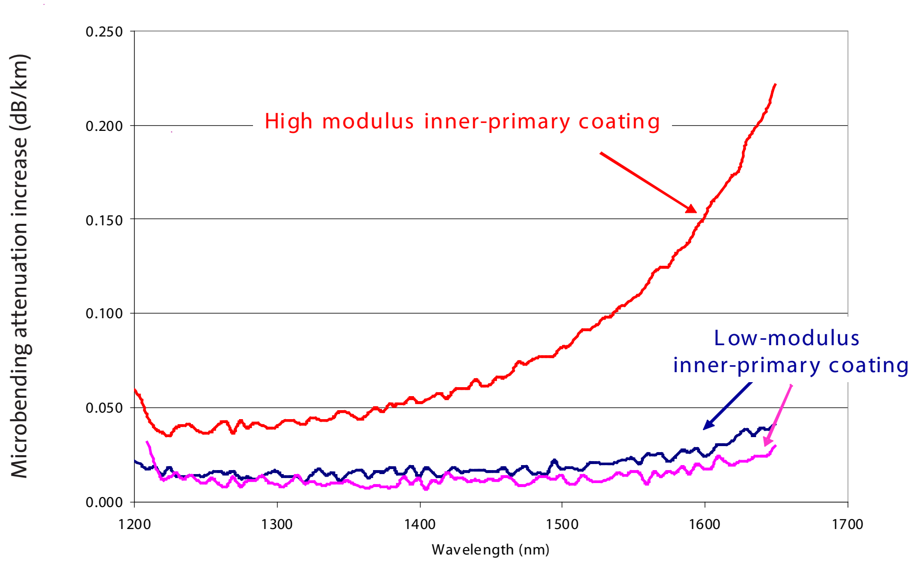
However there are practical limitations to using core radius and refractive index to design improved microbending. They determine the design optical properties of the fiber (dispersion, cutoff wavelength, mode field diameter, even whether a fiber is “multimode” or “single-mode”) and for a given fiber type or product they are bound by industry standards. For example, ITU-T Recommendation G.652, which defines the industry workhorse “standard” single-mode fiber, specifies dispersion, mode field diameter and cutoff wavelength such that the ability to modify a and Δ in equation (3) and stay compliant to that product standard is limited.

The next opportunities to improve fiber microbending presented in equation (3) are the elastic moduli of the fiber and the fiber coating. Current commercial telecommunications grade optical fibers are all silica thus the parameter E_f is not available for design. This leaves E, the elastic modulus of the fiber coating, and indeed it has been shown that by using a lower coating elastic modulus microbending induced attenuation can be reduced.[12]

The most common approach to reducing coating modulus is to lower the inner-primary coating modulus. As seen in equation (3), the key attribute, E, is for the material that surrounds the glass fiber, i.e., the inner-primary coating. In addition, the outer-primary must be a higher modulus material to enable fiber handling and processing.

The effect of changing the modulus of the inner-primary coating is illustrated in Figure 14, which shows microbending test results of ITU-T Recommendation G.652 compliant fibers with high and low inner-primary elastic modulus coatings (and similar outer-primary coating diameters (242 μm vs 245 μm) as well).

The effect of coating modulus on microbending for ITU-T Rec. G.652 compliant fibers. The microbending sensitivity is reduced for the samples with a low modulus inner-primary coating.
Figure 14



Microbending in Industry Standards

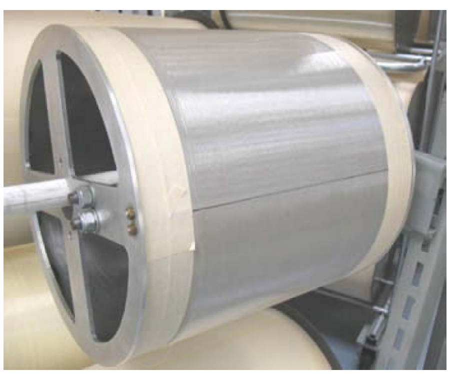
There are no industry standard specifications or test methods for microbending. The IEC has published a document TR 62221 *Optical fibres – Measurement methods – Microbending sensitivity*. This informative Technical Report (i.e., not suitable for specification) lists several microbending test methods common to the industry in the context of "best practices" for evaluating comparative (rather than absolute) performance:
Method A: expandable drum; Method B: fixed diameter drum; Method C: wire mesh; Method D: basketweave.

In general, microbending is measured by applying lateral force to the fiber as a means of simulating a perturbation spectrum and causing microbending. Microbending is determined by measuring the change in transmitted power or increase in fiber attenuation as the load is applied, and is typically characterized as the load is increased.

The methods in TR 62221 work as follows: In the expandable drum method the fiber is wound on a drum whose diameter can be changed mechanically while the fiber is deployed on it, applying a lateral force on the wound fiber. In the fixed diameter drum method the fiber is wound under tension on a drum coated with an abrasive material (e.g., sand paper, wire mesh, etc.). In the wire mesh method, the fiber is pressed against a flat surface covered with a wire mesh. In the basket-weave method, the fiber is "cross-wrapped" on a glass spool and cycled to low temperature so the fiber will contract against the other cross-wrapped layers.

Figure 15 shows photographs of the equipment used to conduct the "wire mesh drum" and "basketweave" microbending tests at Corning's Center for Fiber-Optic Testing laboratory in Corning, NY. Note the basketweave samples require placement in a temperature cycling chamber to conduct the low temperature testing. The common denominator in these tests is the attempt to apply a controlled perturbation spectrum to the fiber in a repeatable manner.

Examples of "wire mesh drum" (left) and "basketweave" (right) microbending test apparatus. For the wire mesh drum test, a wire mesh or screen is attached to the surface of a fiber handling drum. The fiber sample is wound under controlled tension (e.g. 70 g) and the attenuation change is measured. For the basketweave test, the fiber sample is wound on a glass spool, placed in an environmental chamber and temperature cycled according to the specification.
Figure 15



Practical Considerations of Microbending

As seen from the references footnoted in this paper, microbending has been studied since the 1970's. Models to predict it were developed and proven empirically at that time. Yet there are no industry standard specifications or test methods today, almost 40 years later. Why not? So far, microbending testing has proven to be an effective tool for use in developing optical fibers, fiber coatings and cables. But it remains an attribute inappropriate for industry standards or for use in trade and commerce.

This fact was recognized by the experts at the IEC who wrote TR 62221. First, they designated the document a "technical report" rather than a standard, so that its use would be non-normative as opposed to a normative standard. "However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art"….This document, which is purely informative, is not to be regarded as an International Standard."[13]

Next in clause 1 "Scope and object" of TR 62221, the authors clearly stated their position that microbending is not a suitable attribute for trade and commerce: "These methods do not constitute a routine test used in the general evaluation of optical fibre. This parameter is not generally specified within a detail specification."

The great opportunity for a suitable microbending test is a laboratory-scale surrogate test for optical cable testing. There are many more cable products than fiber products in the industry, and producing and testing a developmental cable for each design iteration (fiber count, armored/dielectric, dry/filled) requires significant effort, investment and cost. Reducing the scope of such testing by judicious use of a surrogate fiber based "microbending" test in the lab is extremely attractive.

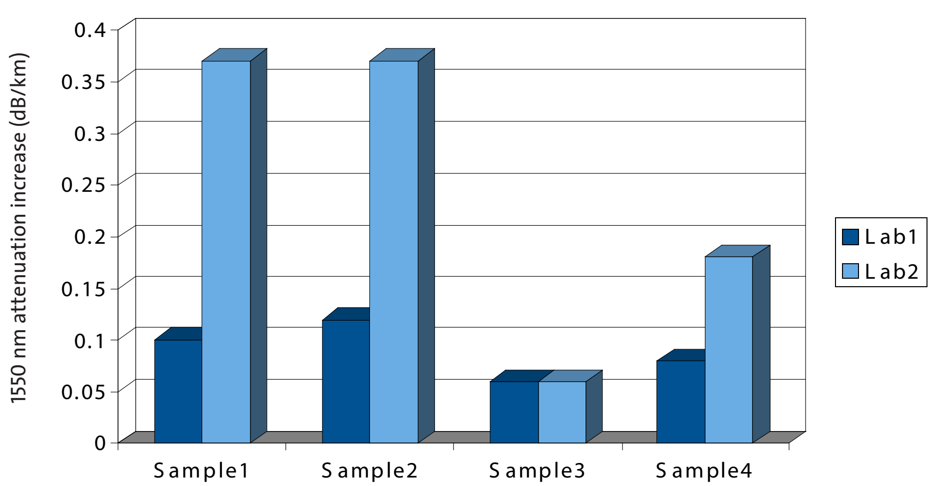
In fact, most optical cable manufacturers who support new product development have developed custom microbending test methods that they believe give them this capability. The four listed in TR 62221 are a sample of the diversity of such methods, but there are many more.

This points to the next problem: Microbending testing does not contain suitable metrology to be defined as an industry standard. The test repeatability is simply not sufficient to use these methods in trade and commerce. Again, this was noted by the authors of TR 62221: "The results from the four methods can only be compared qualitatively." [14] This is why many labs seem to have their own methods: test repeatability is poor between labs, and even within a lab microbending testing must be interpreted directionally and qualitatively rather than as a robust quantitative value. Also, it is likely that a company with an effective internal microbending test would consider it a trade secret and oppose sharing the technique with the industry, i.e., its competitors.

Poor microbending test repeatability is illustrated in Figure 16 below. Two fiber optic test laboratories measured microbending sensitivity using the basketweave test method described in TR 62221 Method D at -60° C. The samples were commercial grade ITU-T Recommendation G.652 compliant fibers drawn on research equipment using commercially available UV curable acrylate coating systems. Each sample represents the same drawn fiber reel, i.e., adjacent pieces of fiber from the same original fiber preform. The two labs are in different companies, and both have a record of participating in open-industry external test programs.

Basketweave method inter-laboratory microbending test comparison. Note the poor agreement between the two laboratories on Samples 1, 2 & 4. While the two labs' results agreed well on Sample 3, anomalies in the results suggest they are the result of test errors.

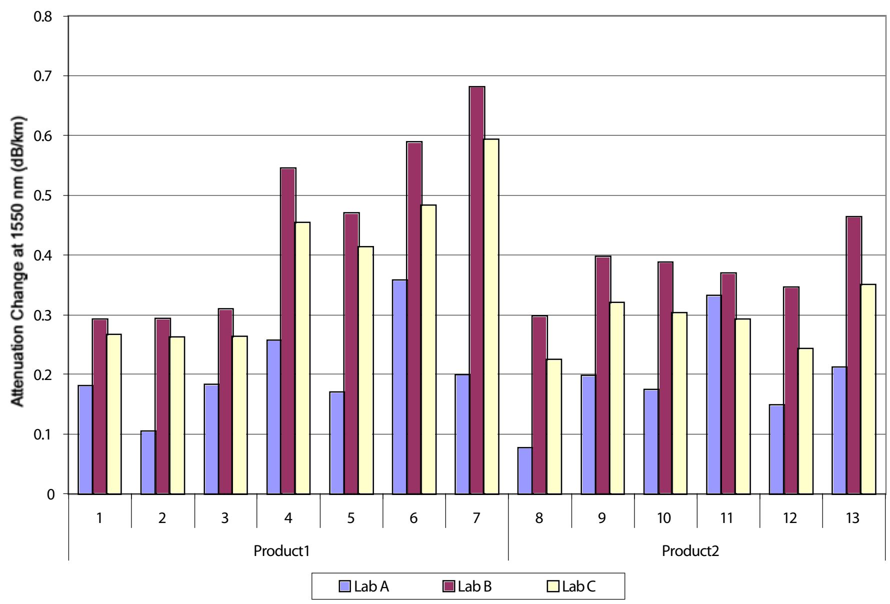
Figure 16



Note the poor agreement between the two labs. Results from Lab 2 can be 3X the magnitude of the results from Lab 1 on the same fiber. In the case of Sample 3, while agreement looked good between the labs, additional results cast doubt on the Lab 2 data: Anomalously, Lab 2 measured a 1625 nm attenuation increase much lower than the 1550 nm increase shown in Figure 16, which is counterintuitive and disagrees with the physics of the test.

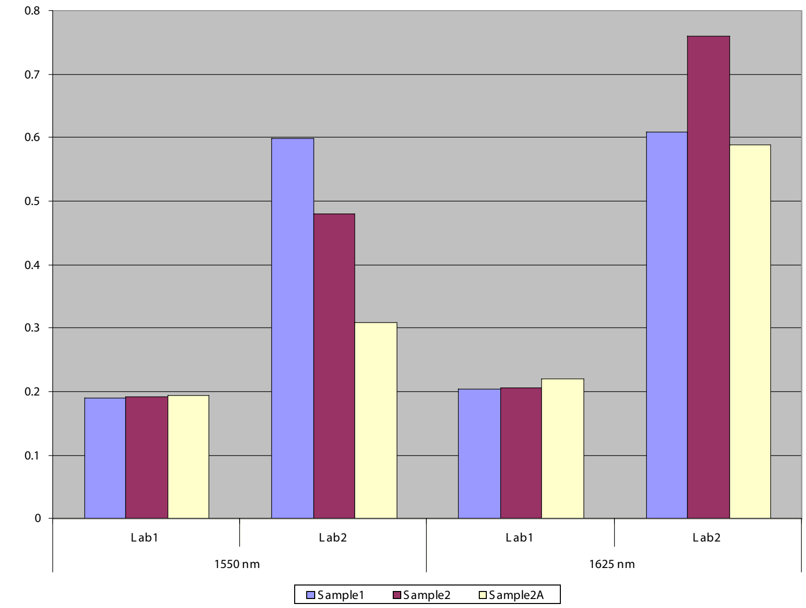
Similar results are shown in Figure 17, this time on two separate optical fiber products (seven samples of one, six of the other) in testing at three different laboratories. While excellent agreement is seen between Lab B and Lab C, Lab A consistently measured lower attenuation increases. Figure 17 simply confirms the conclusion one reaches from Figure 16: it is very difficult to get the same results from microbending measurements conducted at different locations, regardless of experimental controls or laboratory expertise.

Wire mesh method inter-laboratory microbending test comparison. Note that Lab A consistently measured lower values than Labs B & C, despite reasonable agreement between Labs B & C.
Figure 17



Why the poor agreement between these labs? Further analysis shows that the divergence between the Lab 1 and lab 2 results shown in Figure 16 began during sample preparation, even before samples were temperature cycled and the test began. Figure 18 shows the 1550 nm and 1625 nm attenuation measurements after the samples were wound onto the basketweave measurement drums (see Figure 15) prior to deployment in to the environmental chamber and temperature cycling. Note that the Lab 2 processing increased the attenuation on each sample substantially more than Lab 1 (whose results resemble typical pristine fiber measurements at 1550 nm and 1625 nm: 0.191 dB/km and 0.203 dB/km respectively).

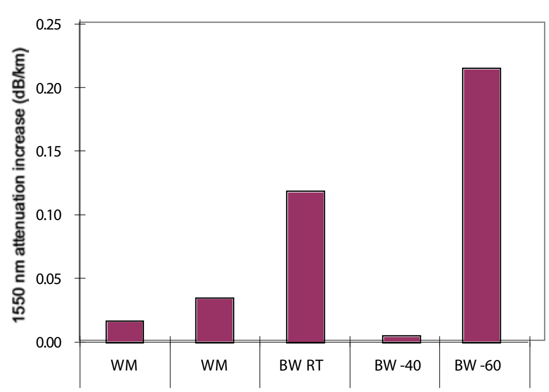
This figure shows the fiber attenuation on the wound, prepared samples prior to temperature cycling reported in Figure 16. Note that Lab 2 measures much higher attenuation after sample preparation than Lab 1. In fact, the results shown for Lab 1 indicate almost no attenuation increase compared to the original value. This suggests that Lab 2 winds the samples with greater variability than Lab 1. This is a likely source of the disagreement in the results shown in Figure 16.
Figure 18



As one might expect from Figure 16 and 17, the agreement when running different test methods defined in TR 62221 is poor as well. Figure 19 presents results for two test methods defined in TR 62221, the wire mesh drum and basketweave methods. These tests were run on the same fibers in the same laboratory, actually drawn from the same perform with the same coating.

The results in Figure 19 are directionally consistent: In the basketweave test the attenuation increases more at -60°C than at -40°C for each sample. However note the disparity between results for the same samples. The two wire mesh measurements are 2X different. The room temperature basketweave result is 3X different than the wire mesh drum result. This disagreement is simply too large to use these methods effectively as an industry standard. Industry standards for attenuation (IEC 60793-1-40) and mode field diameter (IEC 60793-1-45) each describe several methods for measuring their respective attribute. However the test methods are designed so that regardless of which method is used, the same robust repeatable value will be obtained as with any of the other methods – and this occurs in practice. Clearly the methods described in TR 62221 do not meet this criterion.

Microbending test results for wire mesh drum and basketweave methods. Note the poor agreement between the tests. The disagreement is too large to consider these methods as industry standards.
Figure 19



These results highlight the dilemma faced for developing microbending test methods: the compromise between metrology and applicability. The fact that many companies use their own “home grown” microbending tests qualitatively is evidence of the poor lab-to-lab repeatability of these tests – if there was a suitable standard, they would use it. On the other hand, the methods described in TR 62221 are results of efforts to improve the metrology of microbending testing, improving repeatability of the results, engineering efforts to standardize deployment conditions, the perturbation spectra, the force application, etc. As the metrology improves on these common methods, they seem to diverge from providing practical results correlating to actual cable products and use.

In summary, microbending is effective as a surrogate test to predict fiber performance in cable – but it becomes unnecessary once the cable is specified, made and tested. Therefore microbending testing has no benefit in the open market. Specifying and testing the finished products bought by end users is the surest method to ensure compliance with specified product performance and reliability.

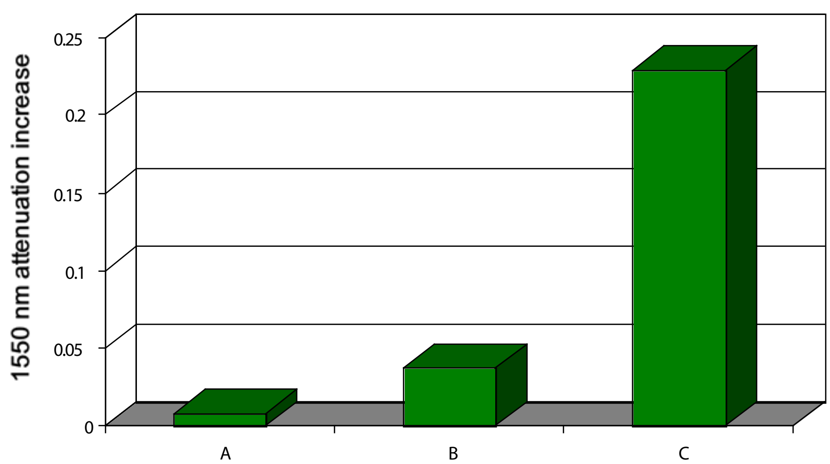
The Role of Coating to Reduce Microbending

The coating is of course an important component of the optical fiber. Poor design, chemistry, or application can degrade performance and reliability. However coating is only one of several contributors to the performance and reliability of the optical fiber product. It works together with the glass fiber and the cable design to deliver a complete finished product with the performance and reliability expected by the market. The interactions between the coating and glass are complex; managing those together as a technology to produce a high quality product consistently takes years of experience in the industry.

As shown in equation (3), the coating can be a key design variable to reduce optical fiber microbend sensitivity. (Note according to Figure 3 and the accompanying theory, the fiber coating does not affect macrobending). But specifying the coating alone is not sufficient to ensure performance and reliability of the entire optical fiber product.

For example, Figure 20 shows wire mesh drum microbending test results for an experimental fiber drawn with an experimental coating to three different configurations. The range of results is wide. So even a coating that delivers superior performance (Sample A) can perform poorly if the final product is not designed correctly – the coating formula itself is not sufficient to ensure top performance.

Effect of coating geometry on microbending. The attenuation of Sample A increased little in this test. Yet the other samples with the same coating in different configurations show more microbending sensitivity.
Figure 20



In the end, optical fiber performance and reliability are a team effort, between the glass and coating, but also including the fiber design, technology and production, to ensure a high performance – high reliability product is delivered to the field. One can’t do it without the others. This is illustrated in Table 1 in which the different contributions to optical fiber performance, usage and reliability are listed for the glass component of the optical fiber and the coating. Both make important contributions, and neither can deliver a complete product on its own.

Table 1 - The roles of glass and coating in an optical fiber

Glass	Coating
Determines the optical properties	*Determines the coating properties*
- Attenuation	- Diameter
- Macrobending & microbending	- Concentricity
- Bandwidth/Dispersion	- Strip force
- Cutoff wavelength	*Determines some environmental performance*
- Mode Field Diameter	- Temperature stability
- PMD	- Humidity stability
Determines the geometric properties	- Water stability
- Diameter	*Visual/perception features*
- Circularity	- Clarity/translucence
- Core-Cladding Concentricity	- Yellowing
Determines the mechanical properties	- Internal defects
- Strength	- Adhesion to the glass
- Fatigue	*Application features*
Determines some environmental performance	- Fiber protection
- Hydrogen aging resistance	- Cabling ability
- High temperature aging	- Microbending resistance
Application features	- Coloring & identification
- Transmission capability	- Environmental stability
- Splice loss	- Handleability
- Connector loss	- Stripping and termination experience

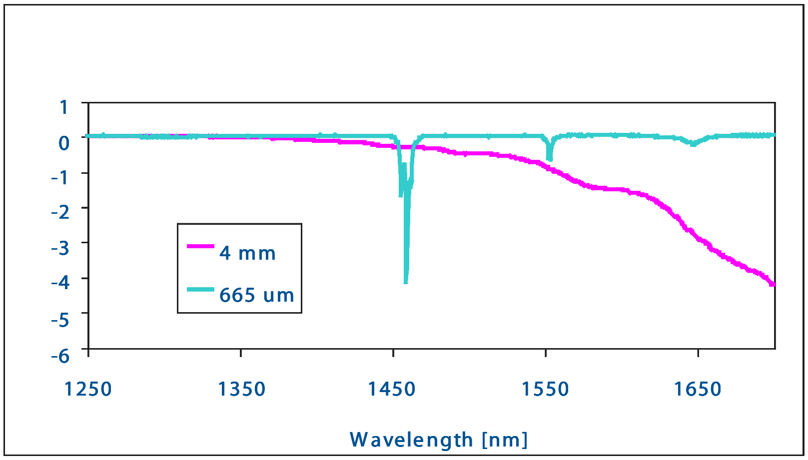
Furthermore, well-engineered cable designs can often be used with more microbend sensitive coatings to provide equivalent performance to better coating with poorer cable designs.

Compare & Contrast Macrobending & Microbending

So what's the difference between macrobending and microbending? As noted above they are different – but they are also the same! Remember that the set of perturbations that cause microbending can be considered as a spectrum. The low frequency/high amplitude portion of the spectrum produces a macrobending type response. The high frequency/low amplitude portion produces the microbending response.

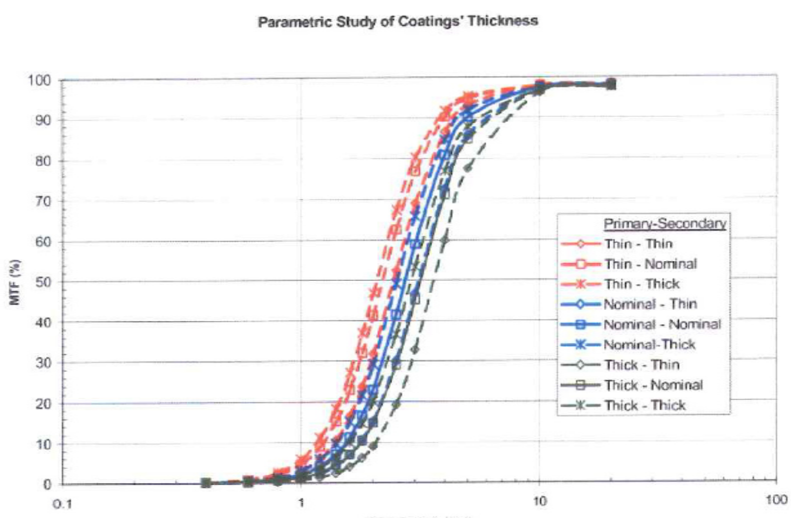
The difference between macrobending and microbending can be seen in the results shown in Figure 21. These results are for rack gear testing with two gears of 665 μm and 4 mm periods. The 665 μm period gear produces the narrow band microbending response similar to the one seen in Figure 11, with the affected wavelengths associated with the 665 μm teeth spacing on the rack gear. However for the 4 mm period rack, the response is much different. The results show the macrobending signature of Figure 4 and Figure 8 with loss increasing exponentially with wavelength. Note that 4 mm approaches the 5 mm radius listed in industry standard macrobending specification ITU-T Recommendation G.657.

665 µm and 4 mm rack loss. The 665 µm gear rack produces, as expected, a clear "narrow band" microbending signature as seen in Figure 11. The 4 mm rack gear produces a clear macrobending signature as seen in Figure 4 and Figure 8.
Figure 21



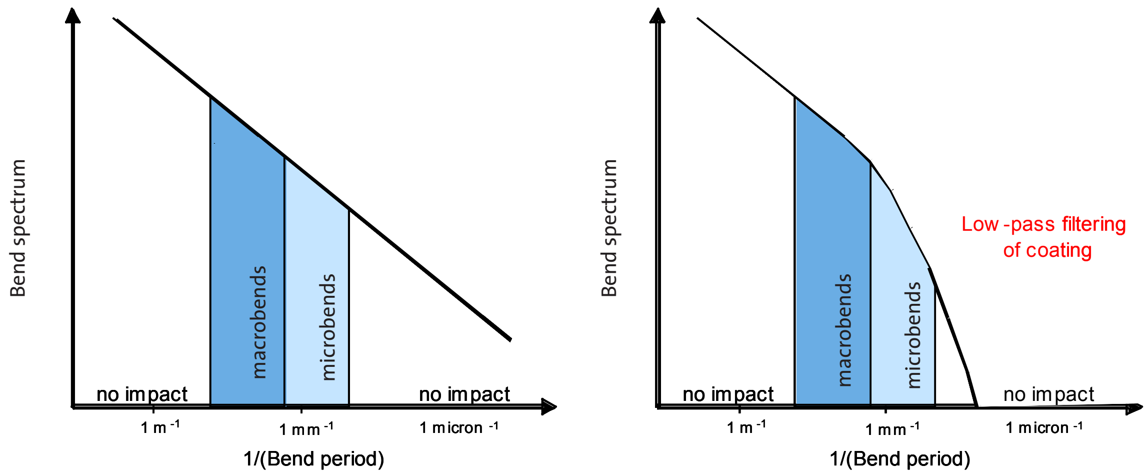
The role of coating in microbending improvement can be considered as a low pass filter to the perturbation spectrum, filtering high frequency perturbations. This is demonstrated in Figure 22 where the mechanical transfer function MTF (ratio of core deformation to coating deformation) for lateral forces is shown for various periods of gear racks and coating geometries used in microbending testing as described above. For short rack periods (high frequency perturbations) the core deformation is only a fraction of the coating deformation. For large rack periods (low frequency perturbations) the core deforms more, especially for periods >1 mm where macrobending dominates. This indicates that coating is not an effective tool to prevent macrobending. Figure 22 also indicates that the impact of different coating geometries becomes less differentiated at the shorter periods where microbending is significant. Even though the transfer of perturbations to the core is low in this microbending regime, it is important to note that even small core deformations of <50 nm can lead to significant loss in a poorly designed fiber profile.

Mechanical transfer function (MTF) for various coating geometries. For larger rack periods, the coating is not able to filter perturbations from the glass, allowing macrobending. Thicker inner-primary coating reduces the transfer of mechanical forces from the coating to the glass, explaining the results presented in Figure 20.
Figure 22



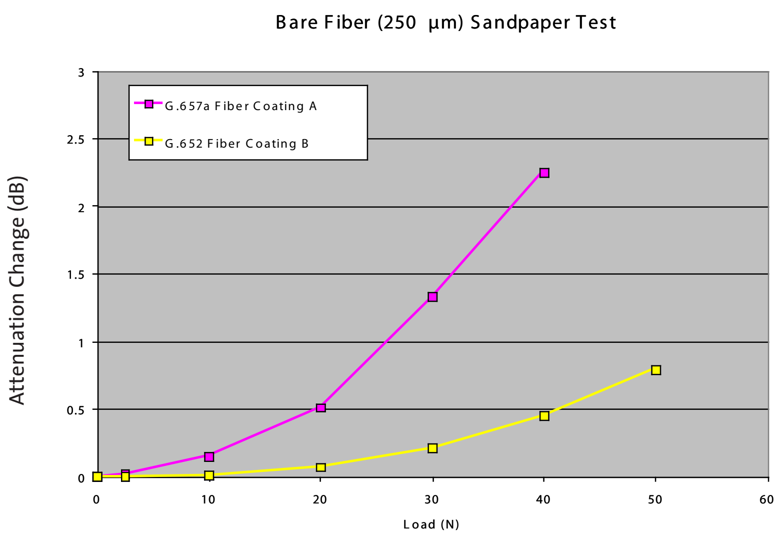
The concept of the coating as a transfer function is demonstrated schematically in Figure 23 where we show the impact of the coating on a schematic of the bend spectrum shown in the right hand plot of Figure 9. Actual perturbation spacing is placed on the abscissa. Note the transition from "microbends" to "macrobends" at ~ 1 mm spacing – remember the macrobending signature of the 4 mm rack data in Figure 21. The left-hand plot shows the bend spectrum of the environment while the right-hand plot shows the low-pass filtering of the bend spectrum caused by the coating. Microbending performance is enhanced as high frequency perturbations are filtered from reaching the core region. Macrobending due to low frequency perturbations is barely affected by the coating.

Schematic figures for the effect of coating on the microbending perturbation spectrum
Figure 23



In fact, when conducting microbending testing, it is almost impossible to apply no low frequency perturbations (i.e., macrobending stimulus) to the fiber sample. This is recognized in the literature.[15] In some cases, the coating can actually overcome any “performance bias” in the fiber inherent in the refractive index profile. Figure 24 presents interesting test results for ITU-T Recommendation G.652 and G.657A compliant fibers. In this test the fibers were laid on sand paper and a lateral load was applied to them while their attenuation change was measured.

Sand paper microbending test results for G652 and G657A fibers with different coatings. The “G.657A Fiber” has a lower MAC design number than the “G.652 Fiber”, which should give it better microbending performance. However the improved coating on the “G.652” fiber overcomes that advantage, making the “G.652 Fiber” less microbending sensitive.
Figure 24

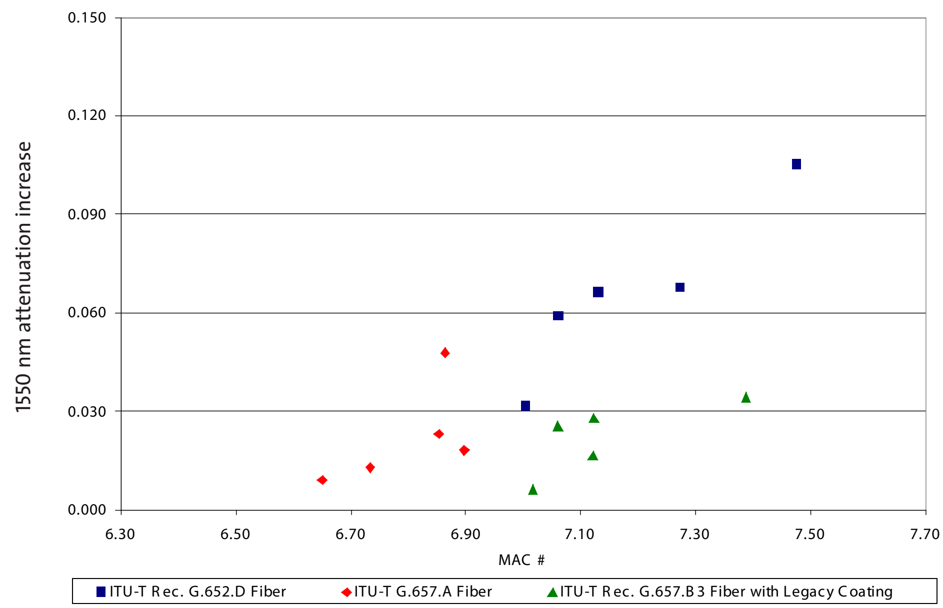


Remember, Rec. G.657A specifies improved macrobending performance that is typically not achievable with a standard Rec. G.652 compliant product design. Note the difference in their 20 mm diameter macrobending test results shown in Figure 4. Based on equation (3) one would expect clear microbending advantage for the Rec. G.657A sample. But the Rec. G.652 fiber sample employed a coating designed for improved microbending performance. The coating improved the microbending resistance to such a degree that the inherent advantage of the G.657A refractive index profile on that sample was overcome, and the Rec. G.652 sample attenuation increased much more slowly as load was applied in the test.

On the other hand, wire mesh drum microbending test results are shown for several fibers and coatings in Figure 25. These contain the same data as Figure 12, except a third data set is added which reports results for testing an ITU-T Recommendation G.657.B3 fiber, specified to the most stringent industry standards, i.e. a 5 mm bend radius. In addition, the Rec. G.657.B3 samples have a legacy coating more sensitive to microbending than the coating on the samples in Figure 12. Yet in this case the robust macrobending resistance of the Rec. G.657.B3 refractive index profile design compensates for a more microbending sensitive coating to produce an overall microbending resistant optical fiber.

This reinforces two critical points of this paper: Microbending test results do not have sufficient repeatability to be used as an effective industry standard for trade and commerce; and while optical fiber coating is important, it is not sufficient by itself to ensure optical fiber performance and reliability sufficient to satisfy the industry's requirements.

Wire mesh drum microbending testing of various ITU-T fiber types with different coatings. As expected (and shown in Figure 12), the microbending induced attenuation increase reduces as MAC number reduces. However the microbending resistance for ITU-T Rec. G.657.B3 compliant fiber is superior to the ITU-T Rec. G.652 and ITU-T Rec. G.657A fibers, so much so that, even with a less microbending resistant coating the fiber still shows less microbending.
Figure 25



Conclusion

Understanding and controlling attenuation change with bending is critical to preserving the superior initial attenuation of the optical fiber. Macrobending and microbending are the two means by which bending can increase the attenuation of an optical fiber.

Fiber macrobending is well developed as a technology. Industry standard specifications exist which link strongly to practical field applications. Standard test methods which produce robust repeatable results – even when different standardized techniques are used – have existed for years. Fiber design options to improve macrobending are understood, and compromises to non-essential attributes are standardized to allow designers flexibility to customize solutions.

Fiber microbending is commonly used as an internal empirical tool within the industry, but it has routinely proved unsuitable for use in trade and commerce. The metrology of microbending testing is not suitable for standardization – test repeatability between methods or among labs is unproven, as is explicitly stated by the authors of IEC TR 62221, the informative test report on microbending. Fiber design rules to improve microbending are known and proven, but are complex, requiring custom solutions not suitable to codify in industry standards.

In particular, specifying a brand of optical fiber coating, or even the properties of that coating, are insufficient to deliver the optical fiber performance and reliability the industry requires and expects. Providing a product that meets those expectations requires an optimized glass and coating product designed, produced and tested with the highest level of technology.

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Corning Incorporated
www.corning.com/opticalfiber

One Riverfront Plaza
Corning, New York
USA

Phone: (607)248-2000
Email: cofic@corning.com

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