

Evolution of 50/125 μm Fiber Since the Publication of IEEE 802.3ae

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Abstract

Since the publication of IEEE 802.3ae, the “10 Gigabit Ethernet (10 GbE) Standard,” development work has continued on high-bandwidth 50 micron (μm) multimode optical fibers for enterprise networks.

Multimode fiber has long been associated with cost-effective installations in premises applications, primarily due to its ability to utilize low-cost 850 nm components. Now, with the advent of the 10 GbE standard, multimode fiber offers an economical route for high bit-rate applications at distances up to 300m.

Although it has been a year and a half since publication of the 10 GbE standard, many industry observers remain skeptical that any 50-micron solution will displace 62.5-micron in the North American market. Similarly, European markets continue to remain focused on obsolete 1300nm LED specifications for 50 μm fiber, rather than higher-performing laser specifications in the more cost-effective 850 nm window. In both cases, the historical reasons for such preferences are valid, but are not fully in line with current industry trends and technology.

Keywords

Multimode; Fiber; EMB; Gigabit; 50 Micron; Microbending

1. Introduction

New multimode fiber solutions focus on high performance vertical cavity surface emitting laser (VCSEL) applications at 850 nm, which require novel approaches to measurement, design, and system modeling that are consistent with the physics of energy distribution and propagation in the fiber. Several industry developments since June 2002 have improved the ability of high-performing 50 μm fibers to be more reliably measured, cabled, installed and deployed for future 10 GbE premises upgrades. Three primary enhancements will be covered in this paper.

- First, the development of calculated effective modal bandwidth (EMBc) provides an accurate assessment of 50/125 system bandwidth performance in 10 GbE systems, and is the only such measurement to return a specific bandwidth value in the familiar MHz.km format. EMBc is standardized in TIA 492AAAC and has been introduced into IEC 60793-2-10.
- Second, Corning has investigated the “engineered link” capability of the high-performing 50 μm fiber, including 10

GbE performance at distances beyond 300 meters and at 1 GbE performance beyond 2,000 meters.

- Third, Corning has developed a greater understanding of the variables contributing to microbend sensitivity of 50 μm fiber in cable manufacturing processes.

These developments will be expanded in greater detail in this paper. The 850 nm wavelength is the only window of operation discussed.

2. Minimum Calculated Effective Modal Bandwidth (minEMBc)

2.1 Bandwidth for Lasers

For decades, multimode fiber has been characterized for performance using the overfilled launch bandwidth (OFL BW) metric, a spatially and temporally overfilled launch that accurately simulates the launch conditions of a Light Emitting Diode (LED). In the late 1990s, as VCSELs became widely available, the TIA FO 2.2.1, “Task Force on the Modal Dependence of Bandwidth,” determined that the customary OFL BW technique would not accurately predict multimode fiber performance when deployed with the narrow-spot size laser sources.

The task force determined that fiber performance with laser sources could be predicted, provided the bandwidth metric appropriately mirrored the actual launch conditions seen by the fiber in the field¹. In addition, it was also learned that when predicting the field performance of laser-based networks it was equally important to understand the encircled flux characteristics of the sources to be included in the system.

2.2 10 Gigabit for Multimode Fiber

TIA FO 2.2.1 (now FO 4.2.1 under the reorganized TIA structure) employed both lessons-learned during the development of the 10 GbE standard. First, they set boundary conditions on the allowable encircled flux for VCSELs supplied for short wavelength operation: < 30% within 4.5 μm radial position and > 86% within 19 μm .

With this definition in place, TIA turned its attention to characterizing fiber performance at a required modal bandwidth value of 2000 MHz.km, which was called “Effective Modal

¹ TIA TSB 62-20

Bandwidth.” Rather than relying on a traditional swept-frequency bandwidth metric, the task force employed a familiar fiber manufacturing process tool, called the “Differential Mode Delay” (DMD) bench. At publication, the 10 GbE standard developed an intricate set of “masks” that used a simplified DMD output, focusing only on fiber modal time delay to return a *pass* or *fail* on whether that fiber would perform at 10 Gb/s over 300 meters.

2.3 DMD Bench Utility

In the January 2003 revision of TIA 492AAAC and TIA FOTP 220, a new, alternative fiber DMD metric was approved that took advantage of additional DMD bench capabilities that were initially neglected.

As shown in Figure 1, at 850 nm the DMD bench input at a given offset launches a 5 μm mode field into the 50 μm core. Per FOTP 220, this ultra-restricted launch is scanned across the entire core endface at a maximum of 2 μm increments, with the ensuing delay of each mode group being measured and stored by the DMD bench.

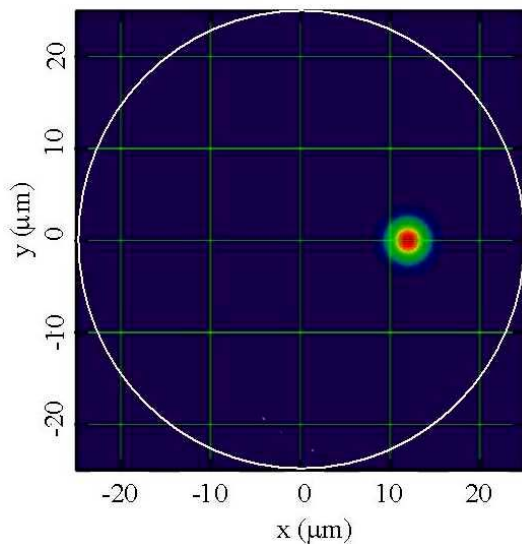


Figure 1. Representative DMD Input

In Figure 1, a single DMD launch is shown at approximately a 12 μm radial offset from centerline, during a scan across the x-axis. The spot size is detailed in three dimensions: radial position on the x and y axes, with input power reflected on the z-axis. For color reproductions of this paper, the Gaussian mode field is represented with peak power at the center of the spot in red, tapering off to yellow, green, and then blue as the input power approaches zero.

A superposition of all DMD inputs, representing a complete DMD measurement, is shown in Figure 2. Note that the same power intensity information is available for each mode group, following the same color scheme from Figure 1.

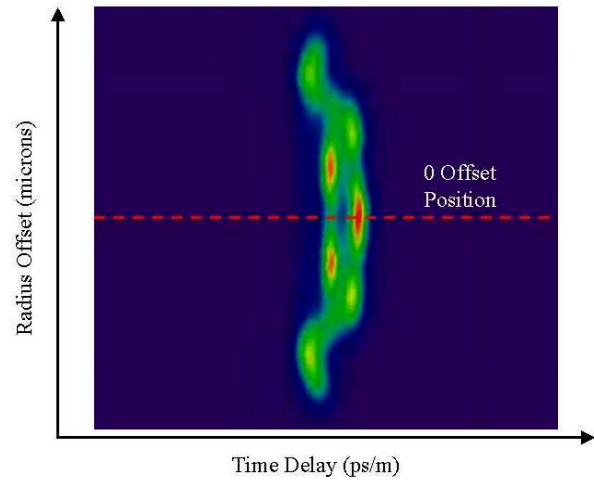


Figure 2. Superposition of DMD Measurements

If Figure 1 is a view of the fiber endface as a DMD measurement is made, Figure 2 can be imagined as the same fiber with the original z-axis rotated to the left. Here, a red dashed line denotes the fiber centerline, where radial offset is now the y-axis. Again, the z-axis reflects power intensity for each mode group by color, and the x-axis is time delay between different mode groups. Since the raw DMD data shown above includes the power transmissivity (or attenuation) by mode group, this plot is sometimes also referred to as “differential modal attenuation,” or DMA.

An enormous wealth of information is contained in the DMA plot; it is a “roadmap” of fiber modal response that includes temporal, spatial, and power contributions.

2.4 EMBC Concept

Whereas the DMD mask method normalizes the raw bench output to focus only on temporal offset, it is possible to employ the additional attenuation information to paint a more accurate picture of how a particular fiber in question will perform with a range of potential VCSELs. The EMBC approach is conceptually given in Equation 1.

$$P(t) = \int U(\rho, t) \cdot \underbrace{2\pi\rho \cdot s(\rho)}_{sc(\rho)} d\rho \quad (1)$$

- t** is time, or temporal delay
- ρ** is fiber radial offset from centerline
- P(t)** is the output pulse from a VCSEL/fiber combination
- U(ρ,t)** is the fiber temporal-spatial response

- $s(\rho)$ is the VCSEL power output as a function of fiber radial offset
- $sc(\rho)$ is the “circular” VCSEL power output, or the radial intensity

Any system’s output pulse shape may be accurately determined if the VCSEL source characteristics are known, combined with the fiber’s temporal-spatial response, and integrated with respect to radial position. Here, the fiber’s heuristic temporal-spatial response, presented above as $U(\rho,t)$, is already measured in great detail at the DMD bench – so let’s define the DMD measurement data as $u(\rho,t)$.

Once that is known, we must then quantify the attributes of potential VCSELS to complete an EMBc calculation. As already discussed, the TIA FO 2.2.1 task force defined an allowable set of radial intensities that compliant sources must meet in order to ensure functional system performance at an EMB of 2000 MHz.km. A detailed definition of VCSEL characterization is beyond the scope of this paper, but is graphically summarized for reference in Figure 3.

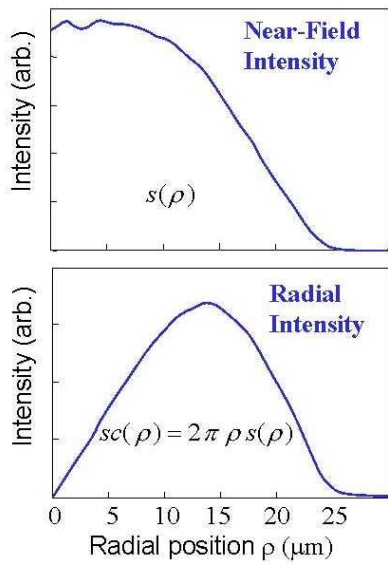


Figure 3. VCSEL Radial Intensity Characterization

In EMBc, radial intensity is used, which is the combination of the discrete power produced at a given radial offset (the “near-field intensity”), multiplied by the annular area at that offset to yield the total effective launched power (the “radial intensity”). Often radial intensity will be plotted as cumulative percentage of power versus offset, which is commonly referred to as “encircled flux.” Radial intensity or encircled flux is the most accurate method of mathematically modeling VCSEL characteristics in multimode systems.

2.5 DMD Mode Power Distribution

A straightforward method of capturing encircled flux in a format compatible with the DMD measurement is to combine the weighted sum of the DMD bench outputs into the fiber under test. Stated differently, the DMD measurement is simply a series of individual launches, each introduced into the core of the multimode fiber under test at different radial offsets. Figure 4 shows the relative mode equilibrium states for each DMD offset at 1 μm intervals from centerline to core-clad interface (0 to 25 μm).

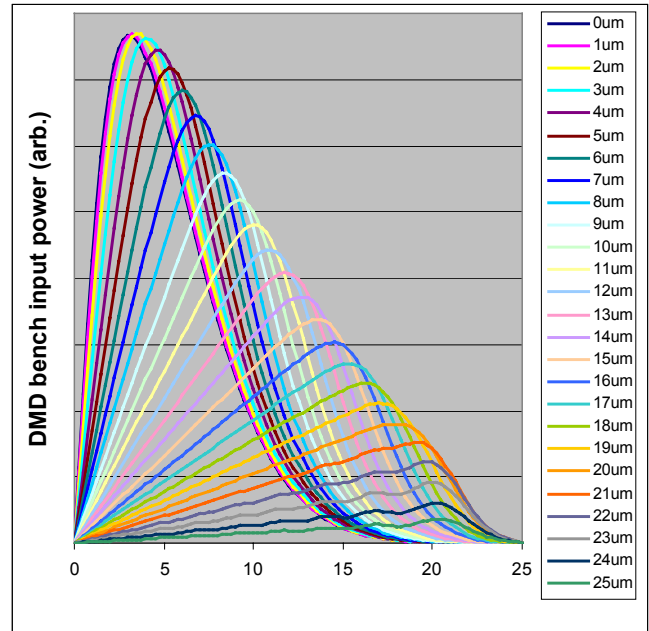


Figure 4. DMD Mode Power Distributions

If each of these DMD bench outputs were integrated and defined as “1,” then a weighting of each offset by some number other than 1 is possible, such that the cumulative sum of the weighted power distributions at each radial offset accurately reproduces the characteristics of any VCSEL. In order to illustrate, let’s first define each potential weighting as $w(\rho)$, where in this case ρ ranges from 0 to 25.

Two examples of modeled versus measured radial intensities are shown in Figure 5, where the cumulative sum of weighted DMD launches (black) closely matches the measured intensity data for a specific VCSEL (red). In fact, the radial intensity of *any* light source may be modeled using the weighted DMD launch approach, which enables the calculation of system EMB as described in the next section.

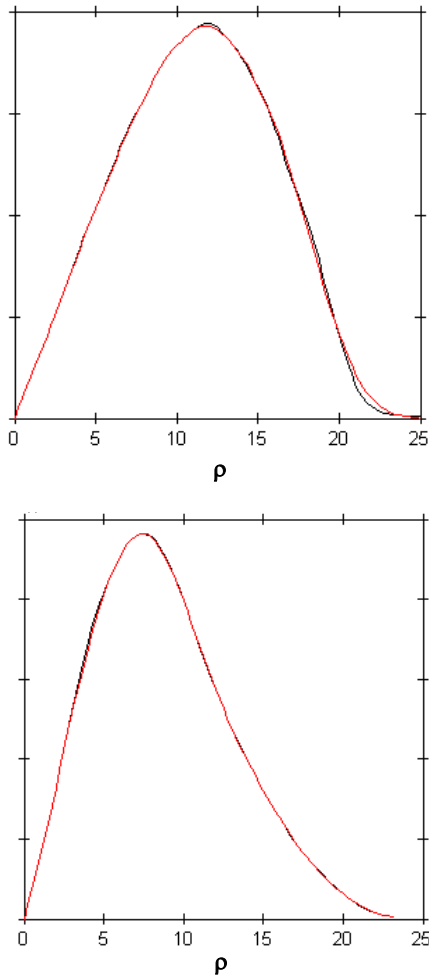


Figure 5. Radial Intensity Data, 2 VCSELs, $w(\rho)$ Sum (Black) Versus Measured (Red)

2.5 minEMBC Calculation

Once $u(\rho, t)$ has been measured and the desired combination of $w(\rho)$ weightings is known, then EMBC may be calculated for any source using the sum function shown in Equation 2.

$$P(t) \approx \sum_{\rho} u(\rho, t) w(\rho) \quad (2)$$

Variables are as defined previously. By using a straightforward summation of the measured values already described, the actual calculation of $P(t)$ may be accomplished in a simpler way than performing the integration given in Equation 1. Putting it together, then, each DMD offset measurement records fiber temporal spatial response, is weighted by an amount sufficient to model a desired source, and is then combined with all other offset measurements to accurately recreate the pulse shape as it would appear in an installed network. The total process is graphically summarized in Figure 6.

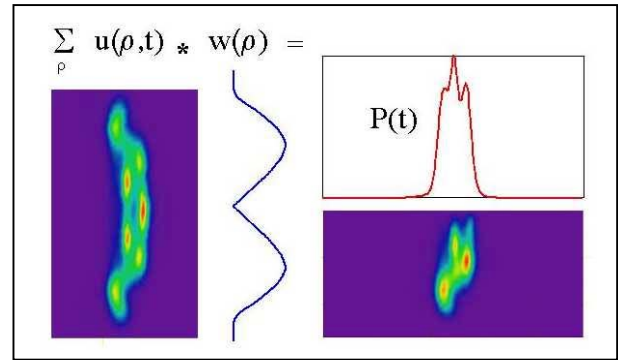


Figure 6. $P(t)$ Derivation from Sum Function

Once the shape of the output pulse is known, then effective modal bandwidth may be computed by referencing the input pulse and using any of a number of acceptable metrics (not addressed in this paper). The output of such a computation will be a bandwidth value in the familiar MHz.km units, representing the system performance of that particular fiber/laser combination

Above, we see one example of calculated EMB, but industry veterans will recognize that product shipped to a specific standard may range widely in attributes within a prescribed set of boundary conditions. To ensure performance of a particular fiber against such a range of VCSELs, EMB is calculated across the entire range of permissible product. As stated earlier, TIA 492-AAAC defined an acceptable source as one which has < 30% encircled flux within 4.5 μm radius, and > 86% encircled flux within 19 μm radius, as measured against the core of a 50 μm fiber. Figure 7 plots 2,000 theoretical sources meeting that requirement, and highlights 10 sources at Corning's Center for Fiber Optic Testing (CFT) that encompass the range of possibilities.

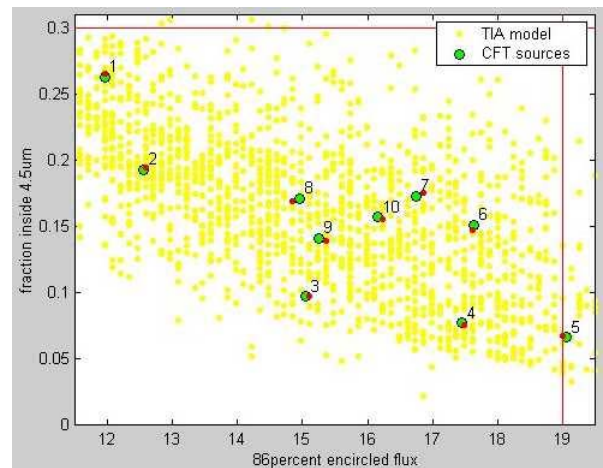


Figure 7. TIA 492-AAAC Compliant Sources

Here, yellow indicates the TIA modeled sources, green indicates CFT sources, and red indicates the nearest match between the two.

If a discrete EMB value were calculated for each of these ten sources on a single fiber, the result would be ten different EMB values (such as 4900, 4238, 3432, 3033, 3096, 3249, 3336, 3667, 3560, and 3445 MHz.km for VCSELs 1 through 10, respectively).

TIA 492-AAAC (and the draft IEC 60793-2-10) specifies ten mode power weightings that are designed to test all portions of the fiber’s modal structure. The *minimum* of 10 calculated values represents the worst-case scenario for that fiber with all allowable sources. In the case above, minEMBc was 3033 MHz.km, meaning when that exact fiber is purchased and installed, the lowest potential EMB in the field will be greater than 3033 MHz.km – well in advance of the required minimum of 2000 MHz.km.

2.6 Future of minEMBc

As described above, the EMBc method is consistent with the physics of energy distribution and propagation in the fiber when combined with a defined source, so it in turn represents a “scalable” bandwidth metric that may be applied to any bit rate or link length of interest. On January 2003, EMBc was standardized as part of IEEE 802.3ae, and is specified in TIA 492-AAAC and TIA FOTP-220. Future standards now have this versatile and useful tool available to ensure fiber performance with their networks.

3. 50 μm Engineered Links

3.1 Minimum Performance?

Another development in 50 μm fiber since the publication of IEEE 802.3ae has been the emergence of branded fibers that support distances in excess of those originally set down. It is widely known that link lengths described in standards publications are often “minimums,” meaning that systems assembled in accordance with requirements will certainly meet the operating ranges published, and may indeed support greater distances. Demonstrations to this end are common.

Let’s look closely at the modeled capability of high-bandwidth 50 μm fiber to understand why extra performance capability is common, and whether it is possible to refine multimode fiber design assumptions to capture that capability in deployed networks.

3.2 Primary Contributing Variables

System performance is determined in large part by the following attributes:

- VCSEL

Center Wavelength	Spectral Width
Transmit Power	Rise-Fall Time
- Fiber/Cable

Modal Bandwidth	Dispersion Slope
Attenuation	Connector Loss

To examine the contributions of these variables, a technical feasibility study was performed using 2000 MHz.km fiber at 1Gb/s over 2000 meters. The GbE² and 10 GbE³ models were used extensively to determine system bandwidth sensitivity for each attribute.

One early item of note was the decreasing correlation between increasing bandwidth and extended link length at very high bandwidth values, as shown in Figure 8.

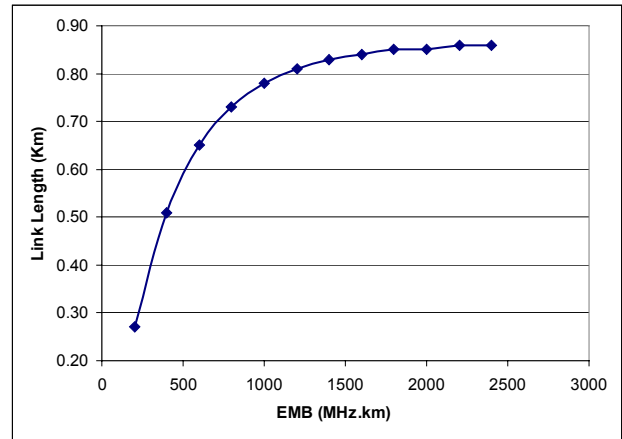


Figure 8. Bandwidth Versus Link Length at 1Gb/s

Here, system link length approaches an asymptotic value of approximately 850 meters at 1400 MHz.km EMB. The reason for this is that modal bandwidth, as a variable, ceases to be a limiting factor in system performance if other system parameters are not also improved. Stated differently, standards organizations assume a worst-case scenario for all components when developing new standards documents – and rightly so. Manufacturers will ship product conforming to standards requirements, up to and including the performance boundary conditions.

However, since manufacturers wish to maximize their yields, they will strive to ensure each and every product they make exceeds minimum performance levels, making the odds of purchasing worst-case components across the board very small. Therefore, it is no surprise that the typical installed network will exceed published minimum values.

For system designers, then, it is possible to set specific boundary conditions to suit specific network reach requirements. Figure 9 summarizes a study of the contribution of variables other than modal bandwidth in systems aimed at 1 Gb/s over 2000 meters.

² “Enhanced Gigabit Ethernet Link Budget Spreadsheet (Version 2),” <http://grouper.ieee.org/groups/802/3/ae/public/index.html>

³ “10 Gb/s Link Budget Spreadsheet (Version 3.1.16a),” <http://grouper.ieee.org/groups/802/3/ae/public/index.html>

Attribute	IEEE 802.3z	...ae	Other		
Bandwidth (MHz.km)	2000	2000	1400	1860	2000
Min Launch Power (dBm)	-9.5	-3.8	-5.5	-5.5	-7.5
850 nm Cable Attn (dB/km)	3.5	3.5	3.5	3.5	3.5
Connectors (dB)	1.5	1.5	1.5	1.5	1.5
Center Wavelength (nm)	830	840	840	840	840
Spectral Width (nm)	0.85	0.29	0.50	0.50	0.55
Unallocated Margin (dB)	Failure	4.6	0.8	2.05	-0.01

**Figure 9. Technical Feasibility Overview
1 Gb/s Operation Over 2000 Meters**

Five potential scenarios are examined. The column under IEEE 802.3z reflects the default model entry values for GbE-compliant VCSELs, cable, and connectors, and clearly does not support operation over 2000 meters. Indeed, as shown in Figure 7, worst-case Gigabit Ethernet components with high bandwidth fiber yield a functional link length of approximately 850 meters.

The second scenario, IEEE 802.3ae, shows the performance of a system installed in accordance with the 10 GbE requirements, but modulated at the target bit rate of 1 Gb/s. Notable differences between the two standards include VCSEL minimum launch power, center wavelength and spectral width. Here we see that 50 μ m fiber not only supports 1 Gb/s over 2000 meters, but does so with 4.6 dB of unallocated margin (enough, perhaps for *another* km of system length).

With those boundary conditions in place, a series of three theoretical intermediate VCSELs were examined, with characteristics between the worst-case Gigabit Ethernet and 10 Gigabit Ethernet sources. Fiber effective modal bandwidth was also varied to further explore the system response to this attribute. Note that for identical VCSELs, shifting fiber EMB from 1400 to 1860 MHz.km did contribute 1.25 dB to unallocated margin – suggesting that bandwidth will continue to play some role even at high values, provided VCSEL performance is adjusted to other than the minimum allowable level. Finally, the fifth scenario shows an estimated “practical minimum” VCSEL that supports 1 Gb/s over 2000 meters, assuming 2000 MHz.km EMB capability. Following the same approach, system assumptions may be refined to estimate the requirements for 10 Gb/s performance beyond 300 meters, or indeed any link length where the fiber and source characteristics are known.

In order to test the model-based technical feasibility study, several ad-hoc tests of 2200 meter, loose-coiled fiber were conducted at CFT from Corning’s available library of 1 Gb/s 850 nm VCSELs and high-bandwidth 50 μ m fiber. Without any special screening of VCSELs or fiber, approximately half of the assembled systems supported transmission with bit-error rates of less than 10^{-12} .

An economic analysis examining the value of designing networks beyond standardized lengths is not addressed in this paper, although intuitively it is valuable to know if it is possible to exceed standards-published minimums for extended link lengths

in specific networks. The ability of network engineers to design “engineered links” of extended distances was demonstrated.

4. Microbend Sensitivity of 50 μ m Fiber

Cable manufacturers often note that 50 μ m multimode fiber exhibits a higher attenuation increase (or induced attenuation) than 62.5 μ m fiber after cabling. Although common cable attenuation specifications place both fiber types at parity, the fact that 50 μ m fiber starts life about 0.4 dB/km lower in attenuation than 62.5 attests to the fact that 50 μ m is generally the more bend-sensitive design. Section 4 of this paper examines three major variables contributing to 50 μ m microbend sensitivity.

4.1 Numerical Aperture (NA)

NA has long been known to be a primary contributor to bend sensitivity across all fiber designs, whether single- or multi-mode. As a rule of thumb, the higher the NA, the higher the refractive index delta between core and cladding, and the better the waveguide properties of the optical fiber. 62.5 μ m fiber, for instance, has a refractive index design delta of 2% between core and cladding, which is double that of 50 μ m fiber. It is primarily the smaller NA of 50 μ m fiber that causes it to traditionally be more microbend sensitive than 62.5 μ m fiber.

Therefore, one potential avenue for improving the microbend performance of 50 μ m fiber would be to increase the refractive index delta. However, such an approach would fundamentally change the modal delay characteristics of the fiber, which have been strenuously optimized to enable 10 Gb/s transmission over multimode fiber as advanced by IEEE 802.3ae. In general, the graded index design of 50 μ m fiber is treated as a constant, and is not a useful tool for improving this particular product’s performance.

4.2 Young’s Modulus

Young’s Modulus of the polymer coating is another commonly known property that affects microbending. The dual coating system with soft inner primary (primary) layer and tough outer primary (secondary) layer is optimal for minimizing microbending loss⁴. In general, a reduction of the inner primary modulus and/or an increase of the outer primary modulus will improve microbending performance, and has been a general trend in the optical fiber coating industry for a number of years. Figure 10 shows representative induced ribbon cable attenuation for various coating systems with a broad range of moduli values.

⁴ D. Gloge. *The Bell System Technical Journal*, 1974, 54 (2), p. 245-262

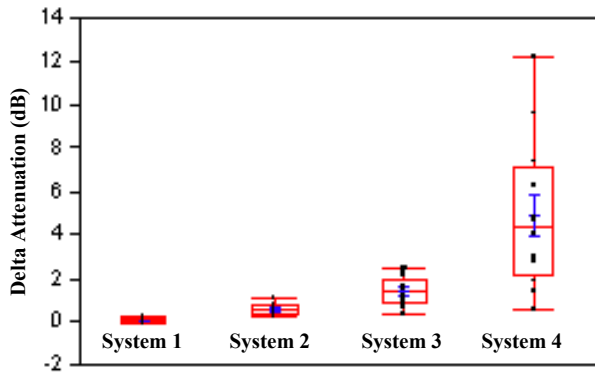


Figure 10. Induced 50 μm Ribbon Attenuation Various Coating Systems

Systems 1 – 4 above include samples from 2 different major fiber manufacturers, and range in properties from low primary/high secondary modulus (System 1), to high primary/low secondary modulus (System 4). The difference in induced attenuation between Systems 1 and 2, which share a common outer primary, illustrates the microbend performance contribution of only a slight reduction in primary coating modulus.

The performance of System 3 reflects the contributions of both a higher inner primary modulus and lower outer primary modulus than System 2.

There are practical limits to exactly how low or high a coating modulus may be changed. Too low an inner primary would fail to hold the fiber in position during normal processing, and too high an outer primary would cause unacceptably high strip forces. Unlike NA, however, coatings do represent an opportunity to improve the microbend performance of 50 μm fiber.

4.3 Inner Primary Coating T_g

Like the coating’s modulus, the glass transition temperature (T_g) plays a role in microbending performance – particularly at low temperatures. T_g is frequently defined as the temperature below which a coating is brittle, and above which it is flexible (although a more accurate definition is based on the fact that at glass transition temperature the coefficient of thermal expansion changes sharply).

As cable temperatures decrease, mismatches in thermal expansion properties between the different materials will in turn cause differential shrinkage, which ultimately impart small microbends to the glass along the length of the cable. We discussed the importance of low inner primary modulus above, so it is desirable, then, to maintain the cushioning capability of that coating even at low temperatures. Therefore, a lower primary coating T_g improves low temperature microbend performance.

When combined with modulus improvements, low T_g values will decrease the bend sensitivity of 50 μm fiber. Understanding these

variables is an important step in making 50 μm fiber easier to process and deploy.

5. Conclusions

This paper has evaluated the most notable improvements to 50 μm multimode fiber since the publication of the IEEE 802.3ae, “10 Gigabit Ethernet” standard. Although 50 μm fiber has long been recognized for its higher bandwidth capacity than 62.5 μm fiber, only recent standards have truly explored the capabilities of 50 μm fiber – yielding a new fiber type that is an order of magnitude higher in performance than previous generations.

With this, the industry is now investing effort in making 50 μm fiber an easily cabled, easily installed and easily managed product for growing premises network needs – with the highest bit rate, longest reach and most cost-effective solutions. Such developments are important now, because long-term bandwidth demand is still forecasted to grow, first in the local access and metropolitan area, then eventually in the long-haul. As this future unfolds, multimode fiber will become increasingly deployed as switching and routing requirements increase at metropolitan area nodes, and as bandwidth demand moves closer to the end user.

6. Acknowledgements

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