Bend Insensitive Multimode Fiber - Is The Reward Worth The Risk?

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Abstract

Bend insensitive multimode fiber (BIMMF) has been receiving considerable attention in both the media and standards bodies. Several manufacturers have announced and released BIMMF products. Each of the new BIMMF designs differs in ways that affect transmission performance and compatibility.

A number of technical challenges inherent in initial proprietary offerings are being examined within standards bodies such as TIA TR-42 and IEC SC86A. These efforts may modify measurements and fiber specifications in attempts to ensure BIMMF designs that optimally interoperate with each other as well as with standard multimode fibers, and smoothly support high data rate applications. This material will provide an assessment of the current situation.

1. Introduction

BIMMF was introduced to the market in 2009 and through marketing efforts has caused the industry to consider its usage. Multiple fiber manufacturers now offer 50 μm BIMMFs of various designs, all providing reduced loss when the fiber is bent. However, the improvement in bend loss performance introduces operational trade-offs and complications with the applicability of several fiber measurements that were not designed for BIMMF.

Representatives of several companies have been examining various BIMMF fiber designs. These examinations have revealed significant issues that must be addressed before BIMMF can be standardized or deployed with confidence. Three categories of issues are currently under investigation:

1) assessing the basic opto-geometric parameters of core diameter and numerical aperture which affect connection loss and compatibility between fiber designs,

2) accounting for the behavior of different modal propagation properties which affect transmission fidelity, and

3) determining suitability and operational limitations if used within launch cords for cabling attenuation measurements.

The presence of leaky modes in BIMMFs causes their characteristics to exhibit a high level of dependence on the length of the measured sample. Leaky modes can travel significant lengths and can mix into bound modes at connections, so their effects on the transmission fidelity of the channel are also of concern. The bend loss performance of BIMMFs exhibit large wavelength dependence which affects their utility within launch cords.

2. Specification Proposal and Application

Table 1 shows the standardized bend loss specifications of traditional 50 μm multimode fiber (MMF) and, in the light blue shaded cells, those proposed to IEC SC86A WG1 in April 2010 [1]. This proposal has remained static while both IEC and TIA have continued to examine the underlying properties of BIMMFs over the past 18 months.

TABLE 1. STANDARD AND PROPOSED BEND LOSS SPECIFICATIONS

Macrobend Loss, max (dB)					
Bend radius (mm)	Number of turns	Traditional 50 μm		50 μm BIMMF	
		850 nm	1300 nm	850 nm	1300 nm
37.5	100	0.5	0.5	no spec	no spec
15	2	1.0	1.0	0.1	0.3
7.5	2	no spec	no spec	0.2	0.5

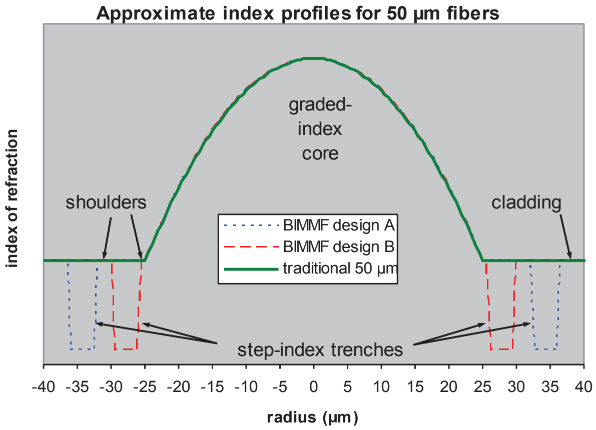
The first specification row defines a 100 turn deployment condition to represent fiber slack storage within splice trays and patch panels of a channel. Note that the proposed specifications for BIMMF are devoid of performance limits in this deployment condition. The second and third rows were proposed to provide values that would relate to performance in locations other than storage spools, as these specifications are limited to just 2 turns. For comparison to these fiber specifications, note that cable is deployed with minimum bend radius based not on this table, but on the outside diameter of the cable, usually 10 times OD[2].

The BIMMF proposal follows the introduction of bend insensitive single-mode fibers that have found solid application in fiber-to-the-home deployments wherein cables are handled like telephone wire, stapled to baseboards and routed around door frames [3]. But unlike the situation for single-mode fibers, there is no corresponding application requiring BIMMF, as MMF is deployed not to the home but rather within enterprises for local area networks (LANs) and data centers. Data center and LAN deployments use cable trays, conduits, patch cord trays, slack storage spools, and rack systems all specifically designed to limit bend radii or mitigate deployment stress and error. Therefore BIMMF offers a solution to a problem that does not normally exist. Instead it is touted to allow forgiveness of mishaps, for example, where a cord may be pinched in a door or placed in tension over a sharp edge. While BIMMF will reduce the loss induced by these stressful events, one must question whether it is better to detect potential fiber breakage before it happens or to be ignorant of the problem until it causes complete failure.

3. Fundamental Differences

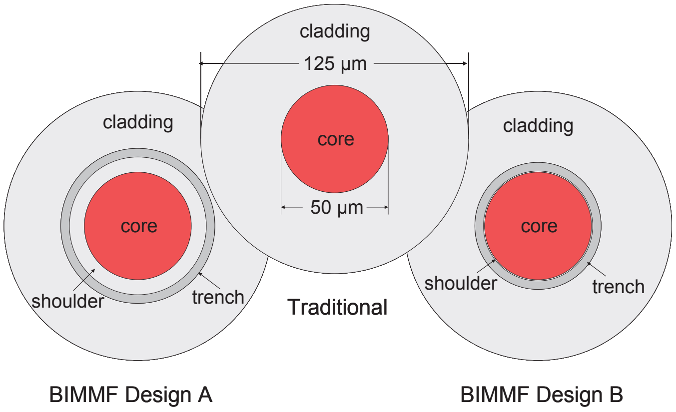
Traditional fiber optic waveguides all share a basic design that consists of an optical core surrounded by a cladding of lower refractive index. The difference in refractive index causes light to propagate primarily within the core. As shown in Figure 1, traditional 50 μm MMF consists of a parabolic graded index core surrounded by a uniform cladding of constant index. BIMMF also consists of a graded index core, but the cladding is modified to contain a ring of lower index of refraction that surrounds the core. The addition of the ring changes the waveguide in fundamental ways.

Figure 1. Traditional graded-index profile with added step-index trenches of BIMMFs



When the fibers are viewed in cross section, as illustrated in Figure 2, the ring structures of the index trenches become clear.

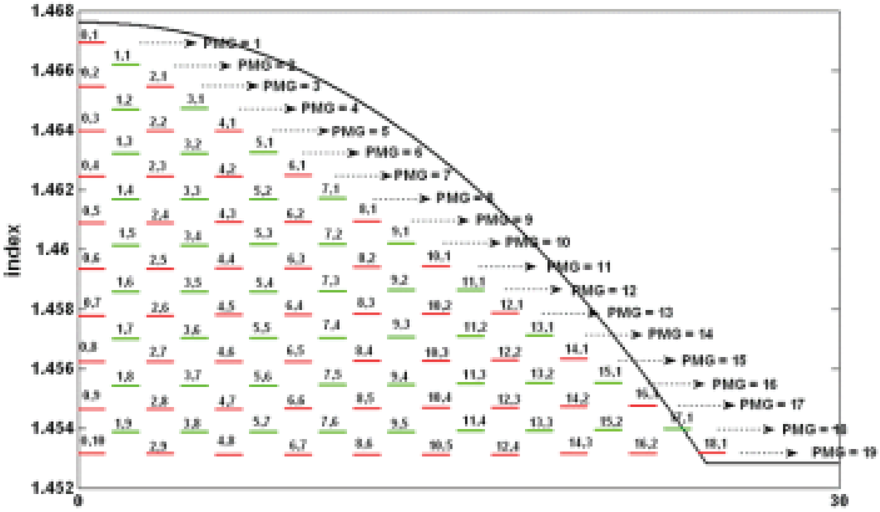
Figure 2. Cross section views of traditional 50 μm MMF and two BIMMF designs



These trenches do two things. First they provide a barrier that resists the loss of light from high-order propagating modes that travel near the core-cladding boundary and leave the core most easily when the fiber is bent. Second they support a new set of modes called leaky modes. Leaky modes are characterized as modes with effective index of refraction lower than the cladding. Leaky modes dissipate very rapidly in a traditional fiber because there is no index structure to support their propagation. It is the presence of propagating leaky modes that is a root cause of some BIMMF issues. Another root cause is the retention of high-order modes which tends to support the build-up of light near the core-cladding boundary.

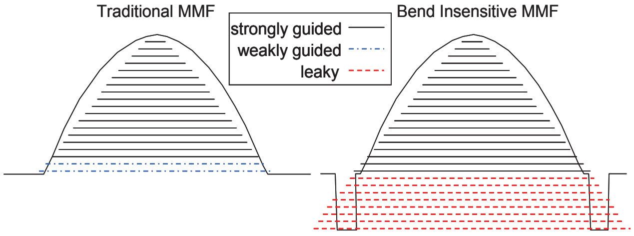
Figure 3 is one way of depicting the modes in 50 μm fibers at 850 nm [4]. By displaying them in this pattern, those that form mode groups of common effective index are shown in horizontal collections with increasing numbers of constituent modes as the principal mode group (PMG) number increases. Higher-order groups have lower effective index, approaching that of the cladding, and travel closer to the core/cladding boundary. The highest groups are therefore the most susceptible to bending loss.

Figure 3. Depiction of principal mode group constituents by effective index, set against index profile



Following this technique, Figure 4 illustrates the difference between the modes of traditional and bend insensitive MMFs. Traditional MMF strongly guides the first 17 PMGs but only weakly guides higher PMGs. BIMMFs strongly guide all the PMGs and also guide leaky modes to varying degrees depending on the design of the trench [5].

Figure 4. Comparison of mode groups in traditional MMF and BIMMF



At least one BIMMF design also differs from traditional MMF in the graded-index portion of the core. Taking the design philosophy that it is better to only support those modes that propagate well in traditional MMF, the graded index delta of this design has been reduced to propagate only 17 PMGs [6]. More about this will follow.

4. Opto-geometric Issues Affecting Connectivity Performance

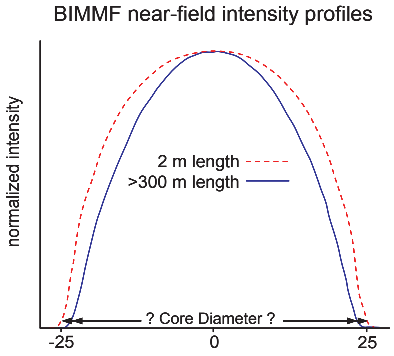
Connectivity performance assessments examine, among other things, the ability to achieve low connection and splice loss. Standardization of measurements for key metrics that affect insertion loss has lead to the ability to achieve good loss performance between fibers of different manufacturers. This is because the measurement conditions were established with consideration of their suitability, repeatability and uniformity for the different fibers under test.

Two important fiber metrics that affect insertion loss are core diameter and numerical aperture. Differences in these metrics cause an inherent mismatch between joined fibers that increases loss. The efforts within standards committees have largely concentrated on exploring and finding resolution to connectivity issues between traditional MMF and BIMMFs, as well as between different BIMMF designs.

4.1 Core Diameter

Core diameter is determined by measuring the intensity of transmitted light from an overfilling source at a sample length of 2 meters [7]. As shown in Figure 5, the extra modes of BIMMFs expand the intensity pattern and then cause it to shrink with increasing sample length as leaky modes dissipate. The measurement standard was not designed to account for this large variation because traditional fibers do not exhibit it. Consequently the value of core diameter of BIMMFs is suspect. For the example BIMMF illustrated, if 50 μm is the measured core diameter of the standard 2 m specimen, the measured value shrinks to 47 μm for specimens of longer length [8]. Note that the standard lower limit on core diameter is 47.5 μm, meaning that the variation in the measured value exceeds the single-sided tolerance [9].

Figure 5. Ambiguity in core diameter due to differences in mode propagation in BIMMFs

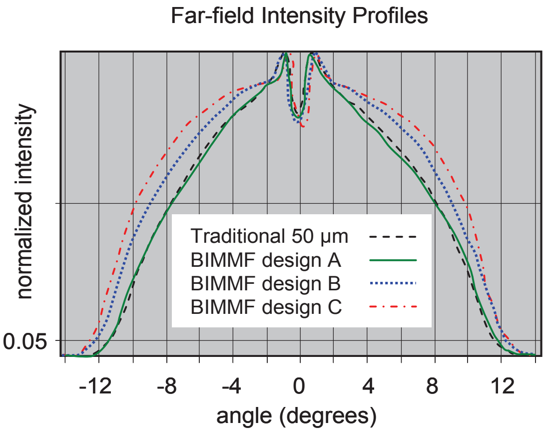


4.2 Numerical Aperture

As with core diameter, numerical aperture (NA) is measured at the output of a 2 m sample excited by an overfilling source. NA is defined by the maximum angle of light that a fiber will propagate. It is also a surrogate for bounding the index delta, the percentage difference between the peak index of refraction and the lowest index of refraction of the graded index core.

Some BIMMF designs place the graded-index core essentially on top of a step-index core formed by an adjacent trench. Refer to Figures 1 and 2. Consequently the far-field transmitted light pattern used to measure NA takes on quasi-step-index characteristics for designs of this type with a broader top and steeper sides [10]. See Figure 6.

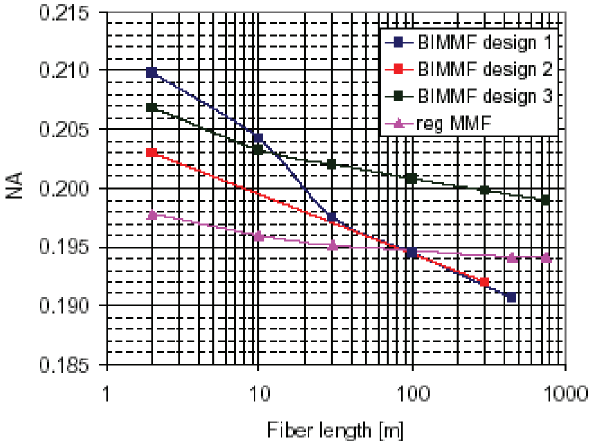
Figure 6. Typical NA of traditional 50 µm MMF and three BIMMF designs



Even though trench-assisted BIMMF is technically a graded-index fiber, the measurement parameters established for NA were set for a traditional graded-index core and do not account for the changes induced by these step trenches. As shown in Figure 6, the standard defines NA at the 5% intensity level [11]. Here two of the BIMMF designs exhibit higher NA than nominal traditional fiber with angles that are up to about 1 degree larger. An increase of 0.9 degrees from the nominal value equates to a value of NA that exceeds the current standard upper limit [9]. The angle increases up to 2 degrees if measured at the 50% level. This change in NA can be expected considering the substantial increase in apparent index delta due to the addition of depressed index trenches.

Similar to the problem with the core diameter, the NA value of BIMMFs are highly dependent on the sample length, as shown in Figure 7 [12], and is another indication that BIMMFs and traditional fibers may not have good mode-field match leading to increased connection loss and larger variability in mixed fiber type channels.

Figure 7. Typical NA of traditional 50 µm MMF and three BIMMF designs

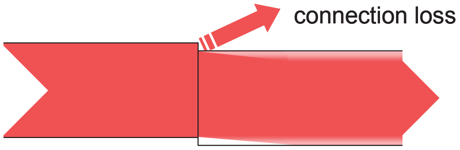


4.3 Compatibility Problems with Traditional MMF

The preceding core diameter and numerical aperture discussions revealed that there are key parametric differences due to differences in mode content between traditional MMF and BIMMF. These differences reduce the match between these fiber types and can lead to elevated connection loss.

Loss at connections occurs when the modes of light in the transmitting fiber do not align or overlap well with the modes in the receiving fiber. As depicted in Figure 8, this can happen when the fiber cores are misaligned due to imprecision in the mechanical geometry of a connection.

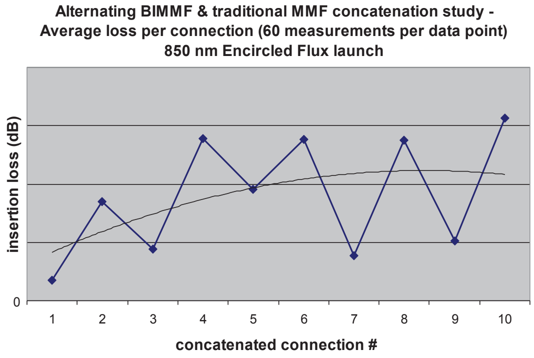
Figure 8. Light escaping from misaligned cores at a connection point



The extra modes and higher NA of BIMMFs will accept more misalignment when receiving from a traditional fiber, driving the connection loss lower. But traditional fibers cannot accept light in these extra modes, driving the connection loss higher. Therefore, what is gained in one scenario is lost in the other in mixed fiber connections. This effect is shown in the measurement results of Figure 9 where a clear oscillating loss pattern emerges from alternating concatenations of BIMMF and traditional MMF. These random-mate measurements were made using a launch condition compliant to the Encircled Flux (EF) metrics of IEC 61280-4-1 edition 2 [13], so are relevant to installed cabling attenuation measurements.

This data reveals two trends that are causes for concern. Firstly, oscillating loss performance creates ambiguity because the expected loss depends on the particular mix of fibers in the channel. Secondly, average loss increases with the number of concatenations. Investigation into the cause reveals a build up of power in the outer radial regions of the core from a combination of mode mixing at connections and high-order mode power retention of BIMMF. In other words, the launch condition evolves towards a more overfilled condition driving up the average connection loss.

Figure 9. Connection loss of concatenations of alternating BIMMF and traditional MMF



The intrinsic differences in mode propagation, along with the expanding launch condition, can be the difference between a passing and a failing channel.

4.4 Compatibility Problems between BIMMFs

As shown in Figure 6, three different BIMMFs exhibit three different far-field intensity profiles, indicating that connection loss issues can be expected not only when mixing with traditional MMF but also when mixing different BIMMFs. Indeed CommScope data bears this out with concatenation studies that exhibit even greater oscillatory behavior and higher average loss than shown in Figure 9.

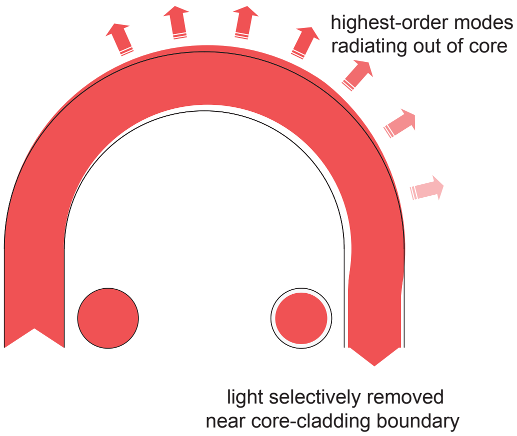
4.5 Proposed Remedies

Several contributions have been submitted to standards bodies to address core diameter and NA measurements of BIMMFs [5, 12, 14, 15]. One line of contributions proposes to use correction factors for both core diameter and NA derived from the difference between short-length and long-length measurements. Another proposes to replace the overfilled launch condition with the EF launch to avoid excitation of leaky modes. The first proposal has been shown to allow corrections to the fiber design targets that reduce or eliminate the oscillatory loss behavior between corrected BIMMF and traditional fibers. The trouble with this proposal is that the correction factors and length of the long-length sample depend on the design of the BIMMF, making its standardization difficult. The trouble with the second proposal is that while the encircled flux launch may succeed at avoiding leaky mode excitation, it also biases traditional fiber values significantly lower. This is not surprising because that launch was not developed for this purpose.

5. Trade-off of Bend Loss with Connection Loss

Light can escape from the core when fiber is bent. As shown in Figure 10, light is selectively lost from the highest-order modes that travel nearest the core-cladding boundary. This is the principal upon which mandrel wrap mode conditioning devices operate.

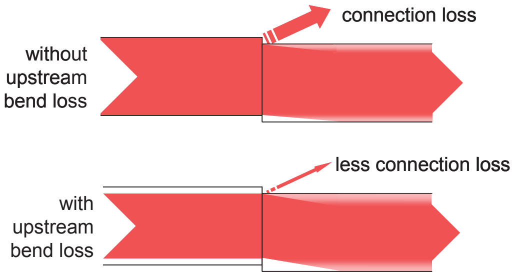
Figure 10. Light near the outer radii of the core is selectively removed by bending loss



A major loss mechanism at connections is axial misalignment of the fiber cores. As illustrated in Figure 8, when the cores are axially displaced the light traveling near the core-cladding boundary cannot couple to the receiving fiber and is lost.

Thus fiber bends and connections tend to lose the same high-order mode light, and loss due to one reduces the downstream loss due to the other. For example, if the fiber is bent sufficiently to lose light, the downstream connection losses will be reduced because the most susceptible light has already been removed as illustrated in Figure 11.

Figure 11. Connection loss reduction due to upstream bend loss

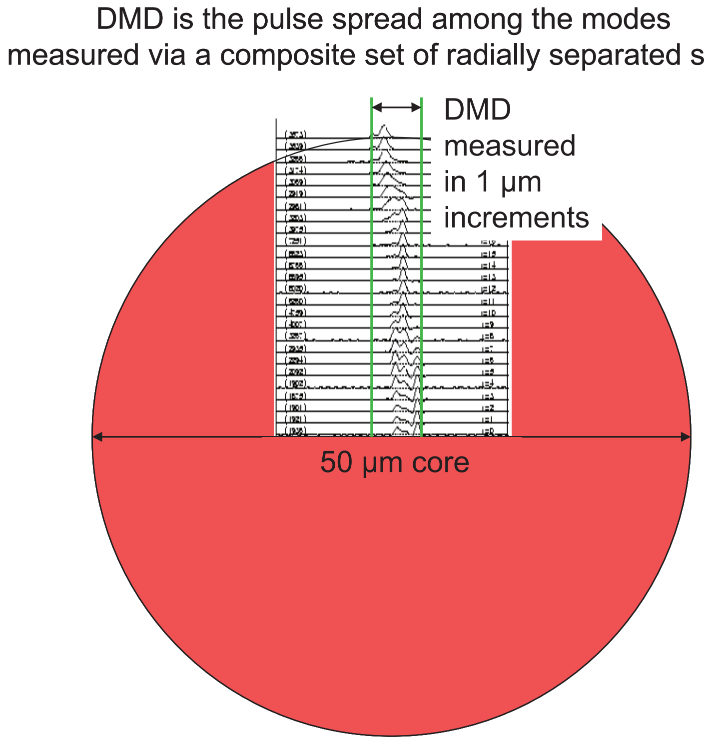


Conversely, if connections strip off high-order mode power, then the downstream loss at bends will be smaller. The two effects trade-off. This fact is not mentioned in literature promoting the benefits of BIMMF. Rather, the loss due to bending is treated simply as additive to the existing channel loss exaggerating the benefits of BIMMF.

6. Bandwidth Measurement Complications

The bandwidth of laser-optimized 50 µm fiber is determined by a series of measurements that characterize the differences in the propagation velocity of the various modes of light [16]. This is called Differential Mode Delay (DMD) and is illustrated in Figure 12. DMD information can be used in two ways to determine bandwidth performance. Firstly, DMD can be directly compared to templates that define limits on the amount of pulse spread over certain radial regions of the core. Secondly, DMD can be converted to bandwidth using weighting functions that represent a collection of laser transmitter light distributions. This is known as calculated Effective Modal Bandwidth (EMBc) [25].

Figure 12. DMD measurement inset on 50 µm core illustrating radial dependence of modes



Both the DMD templates and the laser weight functions were developed using sophisticated computer simulations that analyzed the communications channel performance under certain assumptions [17, 18]. A key assumption relevant to BIMMF is that the simulations fully attenuated (nullified) any light that coupled into the highest two mode groups (PMGs 18 and 19), whether originating from the laser transmitter or from mode mixing at connections. In traditional fibers these groups are weakly bound to the core and dissipate, so the treatment is reasonable. But in BIMMF these groups are strongly bound, meaning that the treatment is no longer appropriate. In fact, owing to their index trenches, BIMMFs also propagate leaky modes, furthering the disparity between their behavior and the simulations. And, as explained in the preceding section on compatibility, mode power can mix into leaky modes even if it is not launched there initially. As a result, the existing DMD templates and laser weights may not be sufficient to robustly determine bandwidth of BIMMFs.

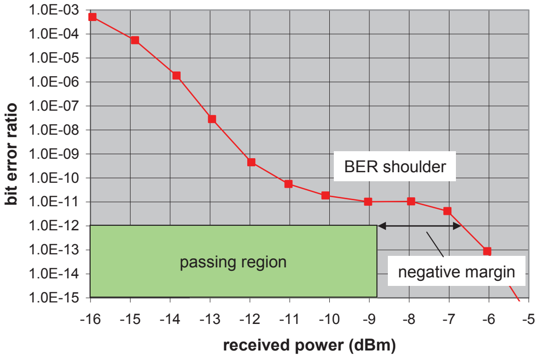
This concern also applies to designs that eliminate PMGs 18 and 19 because the issues arise not from which modes carry the light, but from the fact that more light propagates near the core-cladding boundary in BIMMFs. Reducing the index delta to eliminate PMGs 18 and 19 simply replaces the modes filling the outer radii with the next PMGs 16 and 17. In fact, elimination of two PMGs can inherently reduce mode match between fibers of more nominal design and reduce corrected NA to the lower end of the specification limit or beyond, ultimately increasing compliance problems.

6.1 System Performance Degradation

The bandwidth of a fiber is a surrogate for what we really care about, the ability to resist generating inter-symbol interference (ISI). ISI arises from the spreading of light pulses as they travel down the fiber. Short pulses of light spread into longer pulses and encroach on neighboring pulses. As the pulses overlap, the amplitude difference between the levels of light diminishes and more signal power is needed to maintain an acceptably low bit error rate (BER) [19]. This required extra power is called the ISI power penalty [20].

Higher bandwidth correlates with lower ISI power penalty. However, with BIMMFs characterized with the existing measurement standard this correlation is different than with traditional fibers. Our transmission experiments show BIMMFs that pass the same DMD templates and/or the same minimum EMBc as traditional fiber also exhibit higher error rates than these traditional fibers. A significant percentage of BIMMFs tested show the onset of a BER shoulder, a characteristic where the BER decreases more slowly with increases in signal power [26, 27]. Shoulders can set in above the allowed BER of the application and indicate the onset of infidelity in the channel that can lead to negative operating margin in practice, as shown in Figure 13. It is thought that the more strongly bound high-order modes and leaky modes propagating in BIMMFs are responsible for this degraded performance.

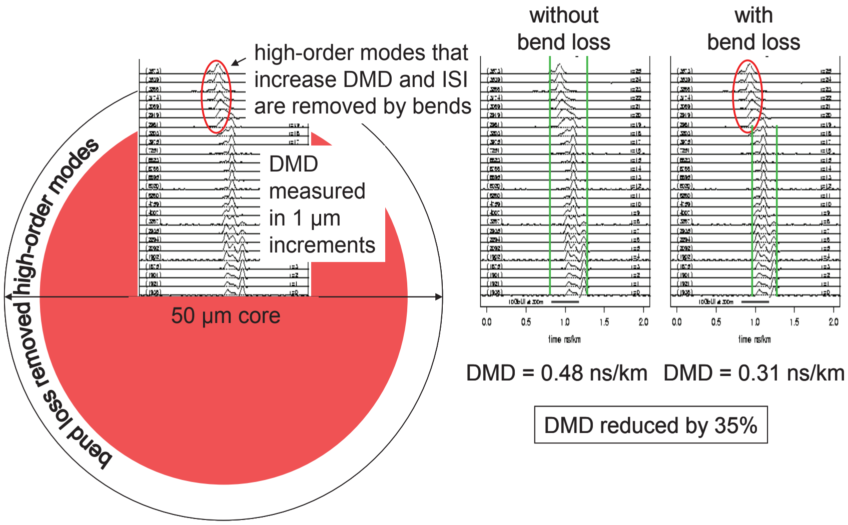
Figure 13. Onset of BER shoulder with BIMMF resulting in negative operating margin



6.2 Trade-off of Bend Loss with ISI Power Penalty

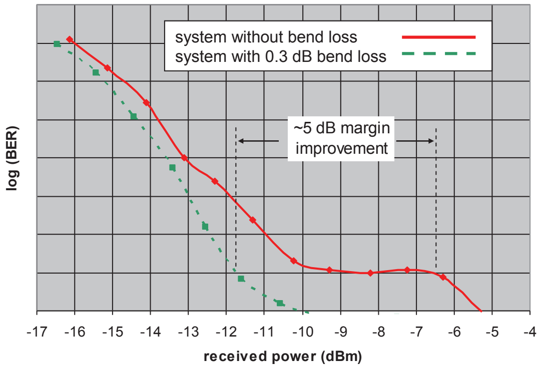
The abrupt rate of change in index of refraction at the core-cladding boundary means that the highest-order modes that travel nearest to this boundary are often the most difficult to control in terms of differences in propagation speed. Consequently the propagation of light in the highest-order modes can often degrade bandwidth and increase ISI power penalty. Bend loss, which preferentially removes light in the highest-order mode groups as previously illustrated in Figure 10, is therefore often beneficial because it can decrease the effective DMD as illustrated in Figure 14.

Figure 14. DMD reduction by preferential removal of highest-order modes by bend loss



The selective reduction in DMD can increase bandwidth and lower ISI and noise power penalties, thus enabling longer length transmission [26, 27]. Given the importance of bandwidth to today's multi-Gigabit data rate applications, this gain from penalty reduction can often be much greater than the power lost from bending. This effect is shown using BER performance in Figure 15 where an improvement in operating margin of approximately 5 dB results from the application of 0.3 dB of bend loss.

Figure 15. Small amount of bend loss producing large gain in system margin



BIMMF is designed to resist bend loss, so while it preserves high-order mode power, it simultaneously cannot provide a benefit from bandwidth improvement for fibers with expanding high-order mode DMD structures. Literature that extols the benefits of BIMMF fails to recognize this trade-off that often favors the use of traditional fiber over BIMMF.

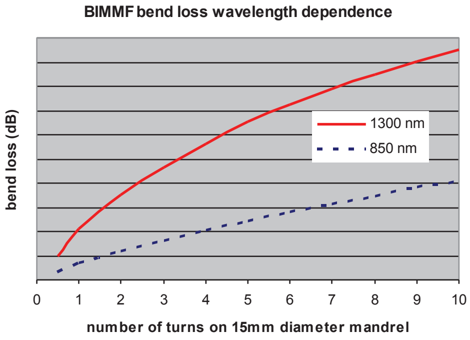
7. Test Set Launch Incompatibility

As can be seen from the preceding discussions on connection loss, the measured loss of multimode systems depends strongly on the distribution of light among the modes. Consequently the fiber industry has recently developed precise specifications on the range of light distribution emanating from a launch cord that can be used to measure the loss of MMF cabling [13]. This specification is a vast improvement over former methods for controlling the launch condition. The precision improvement was driven by the recognition that the available power budget to overcome channel loss has diminished to rather low levels as the data rates of the applications have increased. For example, 100 Mb/s applications like Fast Ethernet permitted channel losses up to 11 dB [21]. But the recently published 100 Gb/s Ethernet standard specifies only 1.9 dB [22].

During the development of the launch specification, considerable effort was expended to define launch condition targets and tolerances that could be met for both the 850 nm and 1300 nm measurement wavelengths using the same launch cord equipped with a simple mandrel wrap mode conditioning device. In fact, the targets were aligned in such a way that for connection loss measurements, the same loss would be measured for the target launch at 850 nm as for the target launch at 1300 nm [23]. By simplifying operations, this alignment benefits a wide range of people including users and installers of cabling systems, connector and assembly manufacturers, and test equipment manufacturers.

Unfortunately these benefits are lost when using BIMMF in a launch cord because its bend loss performance is much more strongly dependent on the transmitted wavelength than that of traditional fibers. For example, on a dB basis, the difference in bend loss with wavelength for traditional fibers is typically only about 10%, but for BIMMFs our data shows it ranges up to 300% or more as shown in Figure 16. This differential is also reflected in the specification proposal submitted to IEC SC86A in April 2010 in which bending loss maxima at 1300 nm were set 250% and 300% higher than at 850 nm, depending on bend radius, as detailed in Table 1.

Figure 16. Bend loss of BIMMF is strongly dependent on wavelength



This means that applying the same controlled bends via mandrel wrap induces much more loss at 1300 nm than at 850 nm. Therefore a common mandrel wrap for BIMMFs likely does not exist, for the mandrel wrap that removes sufficient light to bring an 850 nm source into compliance will remove too much light for a 1300 nm source, necessitating a different test set up [24]. One manifestation of this problem is that test sets that can measure both wavelengths with a single command will instead require separate tests with differing mandrel wraps when using a BIMMF launch cord, effectively doubling the test labor. Perhaps even worse, if this differential is not understood by the test personnel a series of unnecessary remediating actions may precipitate based on erroneous results. Conversely, the measurements could also indicate passing results where the loss would actually be failing under the correct launch condition (i.e. applying an 850 nm mandrel to 1300 nm measurements).

8. Conclusion

While some progress has been made, all significant issues must still be resolved. After 20 months before standards bodies, it is unclear whether a standard for BIMMF will be produced given the possibility that a specification cannot be defined that is sufficiently rigorous to mitigate the technical issues while permitting compliance for the existing BIMMF designs. This is further compounded by the realization that resolution to technical concerns will likely require modification of several measurement standards, in particular those for core diameter, numerical aperture, and bandwidth. Proposals to remedy the first two have significant shortcomings, and the system simulation work needed to answer the concerns of the last has yet to begin.

Unlike bend insensitive single-mode fiber where deployment within homes requires the cabling to handle like telephone wire, there is no application requiring BIMMF. Data Center and LAN deployments use apparatus specifically designed to limit bend radii or mitigate deployment stress and error. Therefore the value of BIMMF is as assurance against the unplanned mishap, such as a cord pinched in a door, not as a solution to support everyday operations. While BIMMF will reduce the loss induced by such a stressful event, one must question whether it is better to detect potential fiber breakage before it happens or to be ignorant of the problem until it causes complete failure.

CommScope has weighed each of these issues, comparing them to the benefits of BIMMF. Given the seriousness and sheer number of issues, we find a large negative imbalance in the trade-off between risk and reward. So while CommScope could readily incorporate BIMMF into its cabling solutions, doing so would compromise our commitment to deliver the most issue-free and trouble-free solutions possible. Consistent with this theme, CommScope remains committed to deliver cabling infrastructures that provide performance benefits most relevant to the applications of today and tomorrow, exemplified by our pioneering OM3 and OM4 solutions.

9. Acknowledgments

CommScope would like to thank the individuals and their sponsoring companies participating in the standards efforts to vet and propose solutions to the issues surrounding BIMMF.

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