White Paper

The straight facts about bend-insensitive multimode fiber

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Management summary

Criticism #1: BIMMF has different core design

The straight facts: The BIMMF offered by R&M is designed such that it exhibits the same graded refractive index core profile as MMF (i.e. same nominal refractive index difference Δ and core diameter). The only difference is the low index trench that enables tighter bends without increasing losses.

Criticism #2: BIMMF leads to higher NA losses

The straight facts: One cannot expect elevated connection losses for intermated MMF and BIMMF when compared to homogeneous mated fibers since both fiber types have the same core index profile.

Criticism #3: BIMMF leads to compatibility issues with MMF

The straight facts: Firstly, the intermating of fiber types has no dominating influence on the expected connection loss. Hence, BIMMF and MMF could easily be mixed in an optical channel without complicating the estimation of losses. Secondly, BIMMF may lead to higher tolerance to possible misalignments when two connectors are mated. This is an additional positive feature for 40 and 100 Gigabit applications when power budget sensitivity becomes a hot topic.

Criticism #4: BIMMF leads to negative impact on system performance

The straight facts: BIMMF has no negative impact on the system performance. It does not lead to higher modal dispersion and therefore neither results in larger power penalties compared to MMF nor in a BER shoulder. Then can clearly be seen from 40 Gb/s BER measurements.

Conclusion

There are many ways how cables can be compressed or pinched in a data center environment. Raised floors and cable trays in data centers can become crammed with cables as new links are added into the network, or cables coming into the rack may experience a bend-radius below the one standardized for MMF despite proper cable management. Bend-insensitive multimode fiber offers here additional security by allowing users to minimize the bend-induced attenuation.

As our testing and the experience of our customers has shown, there are no concerns with using R&M cabling with bend-insensitive multimode fiber in combination with conventional, standard compliant multimode fiber by any manufacturer. BIMMF can therefore help to alleviate the effects of typical data center problems such as compressed cables, and offer at least the same performance as legacy OM3 and OM4 fiber.

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Introduction

Application:	Data center networks, 10 and 40/100 Gigabit Ethernet
Technology:	Multimode fiber cabling
Format:	White Paper
Topics:	Bend-insensitive multimode fiber, multimode fiber, bit error rate
Objective:	To orient readers on bend-insensitive multimode fiber technology and inform them about quality and performance criteria.
Target group:	Data center network managers and installers
Author:	Dr. Thomas Wellinger
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Optical communication systems based on multimode fiber (MMF) are well established in the data center cabling market with a significant yearly turnover which is expected to keep on growing in the coming years. Despite being more expensive than singlemode fiber, MMF cabling is very attractive due to significantly lower transceiver costs as well as larger fiber core diameter and thus larger connectivity tolerances.

The ever growing need for higher transmission speeds in data centers is the key driver for the development of high-speed optical components for local and storage area networks. Such short reach networks are traditionally based on MMF, 850 nm VCSELs and GaAs PIN photodetectors, and currently operate at 10 Gb/s or more. Last year, a key advancement in the networking industry was the completion of the IEEE 802.3ba standard for 40 and 100 Gigabit Ethernet (GbE) [1]. Amongst other things, this standard specifies the 40GBASE-SR4 and 100GBASE-SR10 applications using space-division multiplexing to support data rates of 40 Gb/s and 100 Gb/s on the basis of parallel optics with 10 Gb/s per fiber strand. Depending on the employed fiber type, the new IEEE amendment specifies 100 m transmission over OM3 fiber and 150 m transmission over OM4 fiber. There are also activities of IEEE to standardize 100 GbE over four parallel fibers at data rates of 25 Gb/s per strand [2].

Recently, bend-insensitive multimode fiber (BIMMF) has received considerable interest within the cabling industry due to alleged intermateability concerns which are based on the low refractive index trench around the fiber core in BIMMF and the apparent resulting numerical aperture (NA) and core diameter (CD) mismatch when compared with MMF. It was reported that BIMMF increase the insertion loss in optical connections when mated with MMF that is bent around a mandrel [3]. Other vendors have raised concerns about the system performance degradation when BIMMF is employed [4]. And even in the standardization body, BIMMF fibers are in debate. However, the argument is on how to test optical attributes and how to link these with actual system performance.

Recognizing the complexity of the problem of correct measurements, a careful investigation of the intermateability behavior of MMF and BIMMF and its influence on link performance and bit error rate (BER) is required. This paper will provide experimental data and a detailed analysis of the physical issues arising from deploying a cabling infrastructure that yields in a transmission over intermated MMF and BIMMF cables. The study investigates 40 Gb/s parallel optics performance determined by BER measurements employing commercially available transceiver modules, as well as R&M connector components and fibers.

Criticism #1: BIMMF has different core design

The bandwidth of a multimode fiber is strongly limited compared to singlemode fibers. This is essentially due to the multipath propagation and the resulting group delay spreading among all excited modes. The refractive index profile of the core is the only fiber parameter that sets the electromagnetic properties of the waveguide. In order to compensate for different mode delays multimode fibers are designed with a graded-index profile core as depicted in Figure 1.

The waveguiding effect of optical fibers is due to what is known as total internal reflection, an optical phenomenon that takes place when a ray of light hits a medium boundary at an angle to the normal larger than the critical angle. If the refractive index is lower on the other side of the boundary and the incident angle is larger than the critical angle, all of the light is reflected. It is important to know that the critical angle itself is determined by the refractive index difference of both materials: The larger this difference, the smaller the critical angle gets.

This total internal reflection can only occur where light travels from a medium with a higher to a lower refractive index. If not, a part of that light is refracted and propagates into the medium of the other side of the boundary. Optical fibers employ an optical structure that exhibits a high index material which is surrounded by a low index material, thereby using total internal reflection to confine the light within the high index core and waveguide it through the length of the fiber.

Multimode fibers are specified by ISO/IEC 11801 [5] and IEC 60793-2-10 [6]. The refractive index profile of the core in gradient-index multimode fibers follows a power law function which is optimized to minimize modal dispersion. The cladding index however is constant, as shown in Figure 1.

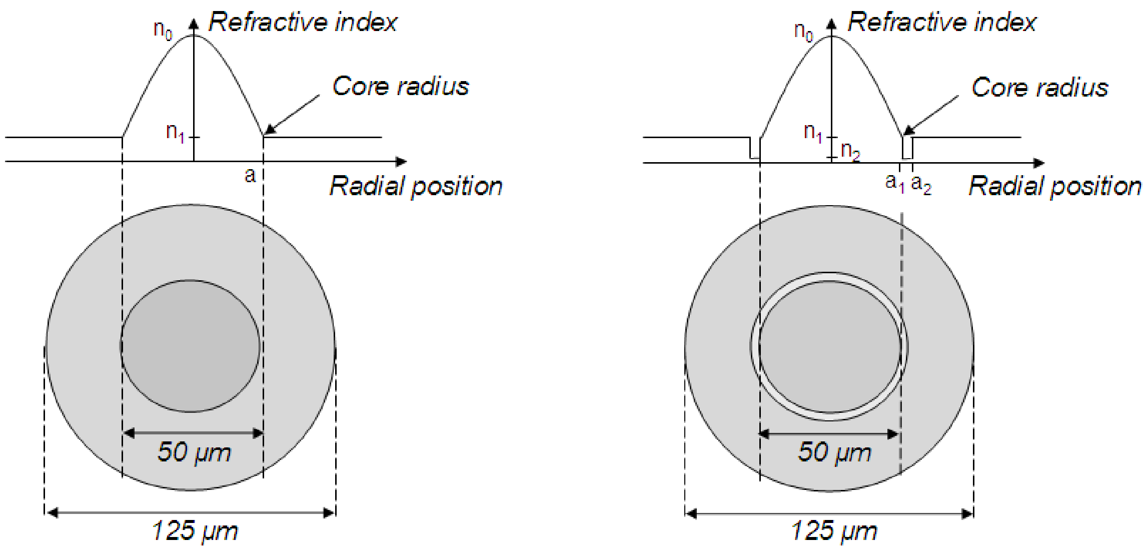

Figure 1 – (left) Parabolic refractive index profile and cross-section of a standard gradient-index multimode fiber. The refractive index of the core is optimized to minimize modal dispersion, while the cladding index is constant. (right) Refractive index profile and cross-section of a bend-insensitive multimode fiber. Following the same core profile, it has lower-index trench of several microns around the core. The outer cladding also exhibits a constant index.

The refractive index of a standard multimode fiber as a function of the radial position can hence be mathematically describes as:

$$n_{MMF}(r) = \begin{cases} n_0\sqrt{1-2\Delta\left(\frac{r}{a}\right)^{\alpha}} & , r < a \\ n_1 & , r \geq a \end{cases} \tag{1}$$

$$\Delta = \frac{n_0^2 - n_1^2}{n_0^2} \tag{2}$$

where n_0, n_1, a, r, and α are the refractive index in the center of the core, the refractive index of the cladding, the radius of the core (typically 25 µm), the radial position, and the power law parameter (typically around 2) respectively.

In the case of BIMMF an additional regime arises which leads to a very similar description:

$$n_{BIMMF}(r) = \begin{cases} n_0\sqrt{1-2\Delta\left(\frac{r}{a_1}\right)^{\alpha}} & , \ r < a_1 \\ n_2 & , \ a_1 \leq r < a_2 \\ n_1 & , \ r \geq a_2 \end{cases} \tag{3}$$

where a_1, a_2, n_2 are the radius of the core (typically 25 µm), the radius of the index trench, and the refractive index of the trench. The important feature here is that $n_2 < n_1$. Typically a_2 is very close to a_1.

By setting an additional low index trench around the core, the contrast between these two refractive indices is increased. As it was stated earlier, a larger difference between these indices lowers the critical angle, thereby also reflecting rays (modes) with a smaller incident angle. Knowing this, it is easier to understand the fundamental idea behind BIMMF, namely to keep modes from being out coupled into the cladding at small bending radii.

Rebuttal #1

The BIMMF offered by R&M are designed such that they exhibit the same graded refractive index core profile as MMF (i.e. same nominal refractive index difference Δ and core diameter) as it is shown in Figure 1. The only difference is the low index trench that enables tighter bends without increasing losses.

Criticism #2: BIMMF leads to higher NA and core diameter losses

The numerical aperture (*NA*) and the core diameter (*CD*) are important optical parameters which describe a fiber's light capturing capability. It is used to characterize launch efficiency, insertion loss at splices and mated fibers, as well as bending performance. Typically, the *NA* of OM3 and OM4 fibers are 0.200 ± 0.015 and given by the expression:

$$NA = \sqrt{n_0^2 - n_1^2} = 0.200 \pm 0.015 \tag{4}$$

The *NA* is thus a surrogate for the index delta between the highest and the lowest refractive index in the core, as defined in equation (4). The *CD* is the diameter of the graded-index core. The *CD* of OM3 and OM4 fibers are 50 µm ± 2.5 µm.

Under standardized *NA* measurement methods (IEC 60793-1-43) [7], input optics are employed which create a radiance spot larger in diameter than the fiber endface and thus much larger than the core diameter. However, this launch condition has been proven inadequate for characterizing VCSEL-based performance which concentrates the light pulses into a much smaller area within the fiber core. In combination with BIMMF, this measurement method overestimates the refractive index contrast between the core and the surrounding trench and cladding, and hence yields an *NA* larger by about 0.008 compared to MMF. Similarly, the standardized *CD* measurement methods (IEC 60793-1-20) overestimates the *CD* of about 1.0 µm.

It is true that an increase in refractive index contrast translates directly into a higher *NA* as light rays within the fiber can be waveguided at greater angles and still be totally internally reflected as illustrated in Figure 2. Thus, high order modes will be more tightly confined in BIMMF whilst experiencing sufficiently high differential attenuation in MMF. However, this assumption only holds as long as all such modes actually transport energy. The use of a VCSEL on the other hand, will only excite a few of those modes and thus renders the information of the overestimated *NA* as irrelevant.

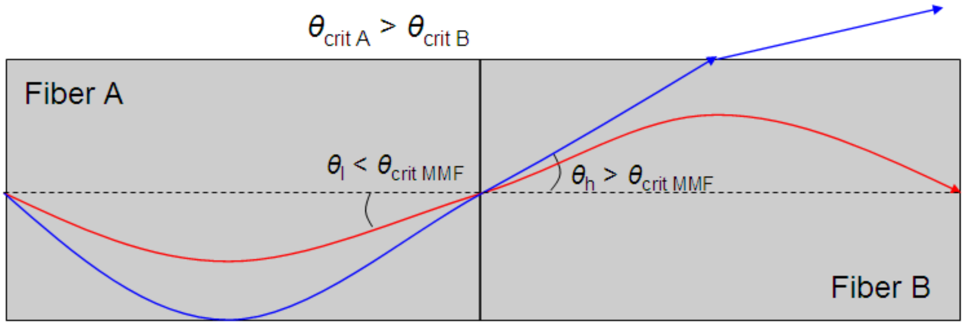

Figure 2 – Schematic illustration of a mismatch in *NA* when mating a large *NA* fiber (Fiber A) to a small *NA* fiber (Fiber B). Since Fiber B has a smaller *NA* and hence a smaller critical angle θ_{crit} for total internal reflections, some higher order modes will not be coupled in and be lost instead. This kind of power loss is referred to as *NA* loss. However, there is no such *NA* loss for low order modes.

Figure 3 presents the *NA* histograms for two different measurement methods. The right hand histograms come from refractive index profiles measured on fiber performs, that is before the fibers are drawn. Both distributions are reasonably overlapping, highlighting that both multimode products – MMF and BIMMF – have the same delta core height as explained in the preceding section. The left hand histograms report the *NA* distributions measured over 2 m fiber samples for MMF and BIMMF. Here one can observe a significant difference among the two distributions, and a 0.008 offset is obvious. This bias arises from so-called leaky modes [8]. A leaky mode is a mode that gradually "leaks" out of the fiber core as it travels down it, being very strongly attenuated even if the waveguide is perfect in every respect.

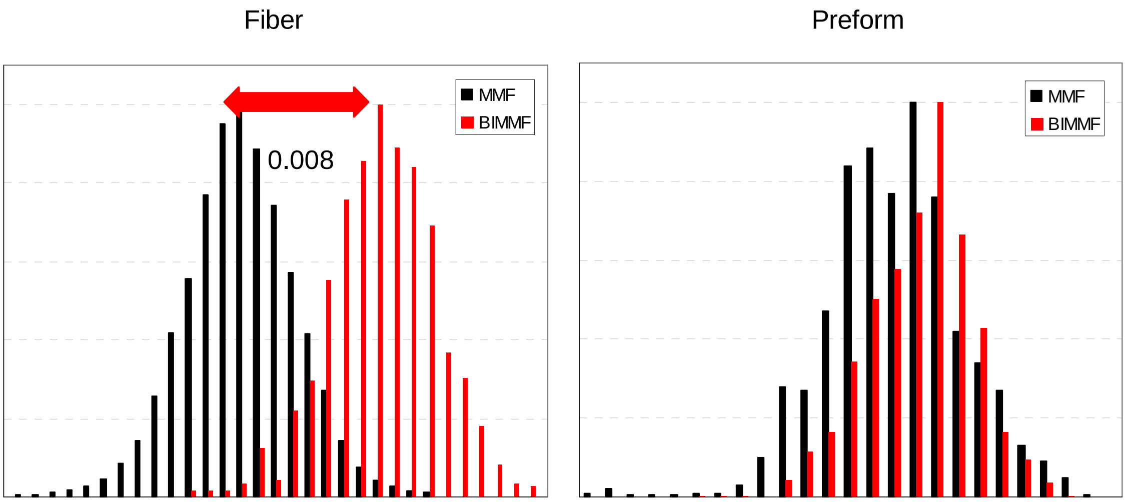

Figure 3 – Normalized probability distributions for conventional and bend-insensitive multimode fiber (left) when measured on fiber and (right) when measured on preform. While a difference of 0.008 in average *NA* can be observed between MMF and BIMMF when measurement is performed on the fiber under overfilled launch condition, the data shows no significant difference when measurement is conducted on the preform.

At a connection, the amount of optical power transferred from one fiber to the other is determined by the overlap integral of the optical modefields in the two fibers. Quantification of this overlap function is complex and affected by waveguide and especially core design, lateral and longitudinal offset of the fibers, and angle of intersection between the fibers. It should now be clear that there are no mode-field shape differences between both fiber types as they exhibit the same core design.

Rebuttal #2

Hence, one cannot expect elevated connection losses due to an *NA* mismatch for intermated MMF and BIMMF when compared to homogeneous mated fibers.

Criticism #3: BIMMF leads to compatibility issues with MMF

All criticism of BIMMF is based on the wrong presupposition of a larger *NA* and *CD* compared to conventional MMF. A logical following is to stress that BIMMF will accept more misalignment when receiving from a MMF, yielding a reduced insertion loss. On the other hand, MMF cannot accept light in these higher-order modes, resulting in increased insertion losses. Consequently, one would expect an oscillating loss pattern from alternating concatenations of BIMMF and MMF [9].

To investigate the mating behavior, compatibility tests were carried out using an 850 nm LED source concatenated with a mode conditioner. All fiber samples were connectorized by R&M MPO patchcords of 35 meters and were assembled and measured in a random-mated fashion. The average loss results are shown in Figure 4 and show no oscillating behavior. Instead, the insertion loss seems to be dominated by the connector quality.

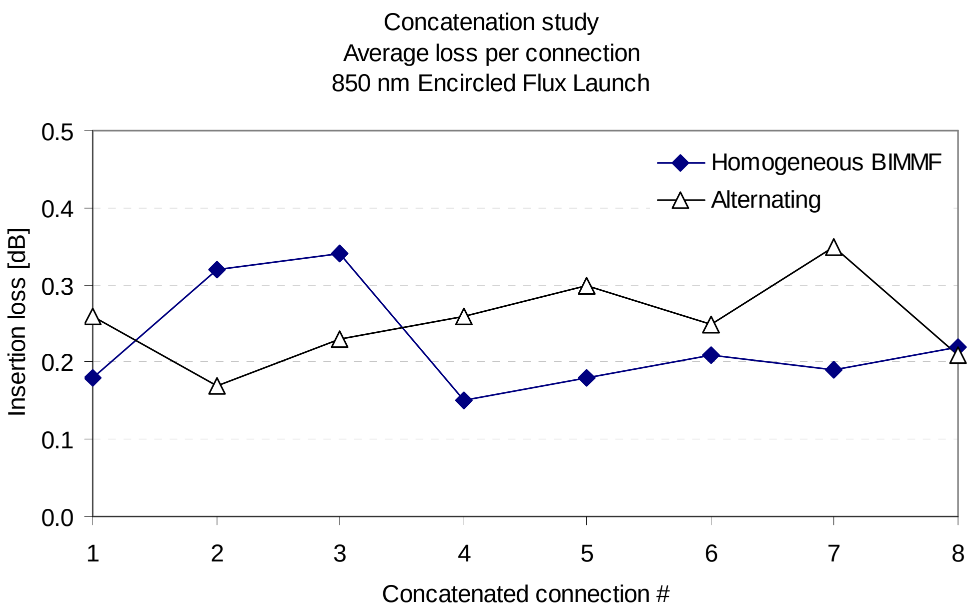

Figure 4 – Individual connection loss of alternating concatenated BIMMF and MMF cables of 35 m length. The varying insertion loss does not follow an oscillating pattern.

Rebuttal #3

The data reveals two interesting points. Firstly, the intermating of fiber types has no dominating influence on the expected connection loss. The oscillating behavior as observed in [9] is likely a matter of *NA* and *CD* mismatches between fibers in the link that is not BIMMF specific. Hence, BIMMF and MMF could easily be mixed in an optical channel without complicating the estimation of losses. Secondly, BIMMF may lead to higher tolerance to possible misalignments when two connectors are mated. This is an additional positive feature for 40 and 100 Gigabit applications when power budget sensitivity becomes a hot topic.

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Criticism #4: BIMMF decreases system performance

Current 100 Gb/s and 40 Gb/s MMF parallel optics links are based on the recently published 100GBASE-SR10, 40GBASE-SR4 standards at 850 nm for transmission lengths of up to 150 m in OM4 fibers [1]. The study of BER performance of BIMMF and MMF in 40GBASE-SR4 systems was carried out with the experimental setup shown in Figure 5. Commercially available 40GBASE-SR4 standard transceivers are connected by a channel under test (CUT). The basic penalty measurement includes a variable optical attenuator inserted prior to the receiver via two sets of 3 meter long fan-outs, to determine the BER as a function of the received power. The resulting data plots are often called waterfall curves. For high attenuations/low received powers, the optical eye exhibits a narrow opening and the BER is high. For increasing received power, the improvement of the BER depends on the shape of the eye which itself is determined by fiber characteristics such as chromatic and modal dispersion. These two effects are the most dominant factors leading to intersymbol interference (ISI). However, for BER around and below 10^{-12} other noise effects such as modal noise, RIN, MPN or reflection noise may influence the performance. Horizontal shifts between waterfall curves indicate ISI of differing intensities, e.g. the more a curve is shifted to the right, the stronger the signal impairment through ISI.

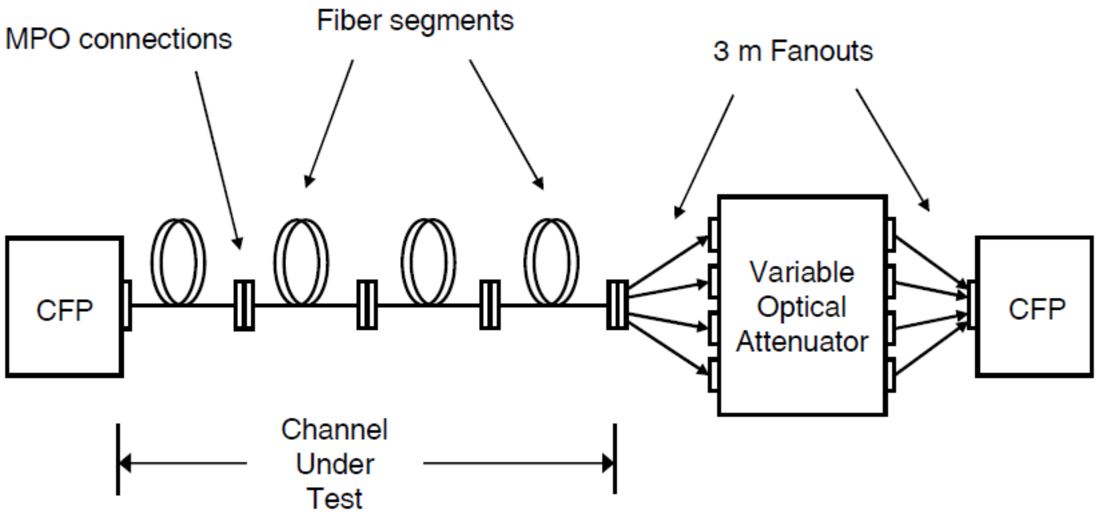

Figure 5 – Experimental setup for evaluating the optical channel. Note that this channel can either consist of only BIMMF, or only MMF, or intermated MMF/BIMMF segments. The bends within the CUT are optional.

For the IEEE 40GBASE-SR4 application the channel insertion loss maximum is 1.9 dB for OM3 fiber and 1.5 dB for OM4 fiber [1]. During the course of this study CFP modules are used to launch the optical signal into the channel which consists of several OM4 cables of differing lengths. These cables can consist of MMF or BIMMF, and are studied in various intermated configurations as well as in homogeneous MMF or BIMMF channels.

So far, there are two standardized methods of characterizing the performance of multimode optical fibers, i.e. the measurement of differential mode delay (DMD) and the determination of a calculated effective modal bandwidth (EMBc). Both test methods aim at determining the modal bandwidth. Another way of testing the fiber performance which is also much closer to how the fiber link is actually used, is the BER measurement. Experiments have shown a high degree of correlation between DMD test and

EMBc results and BER measurements [10]. The BER is the ratio of the number of measured error bits divided by the total number of bits transmitted in a given period of time.

The modal bandwidth of a multimode fiber is really another way of characterizing the fiber's ability to resist generating inter-symbol interference (ISI). ISI arises from the dispersion of light pulses as the propagate down the fiber. Short, separated light pulses of individual bits spread in time and start over-lapping with light pulses of adjacent bits. This can happen to such an extend that it may not be possible for the receiver to distinguish an 0 bit from a 1 bit, as schematically shown in Figure 6. To avoid such an effect, more signal power is needed to maintain an acceptably low bit error rate (BER). This required extra power is referred to as the ISI power penalty [11].

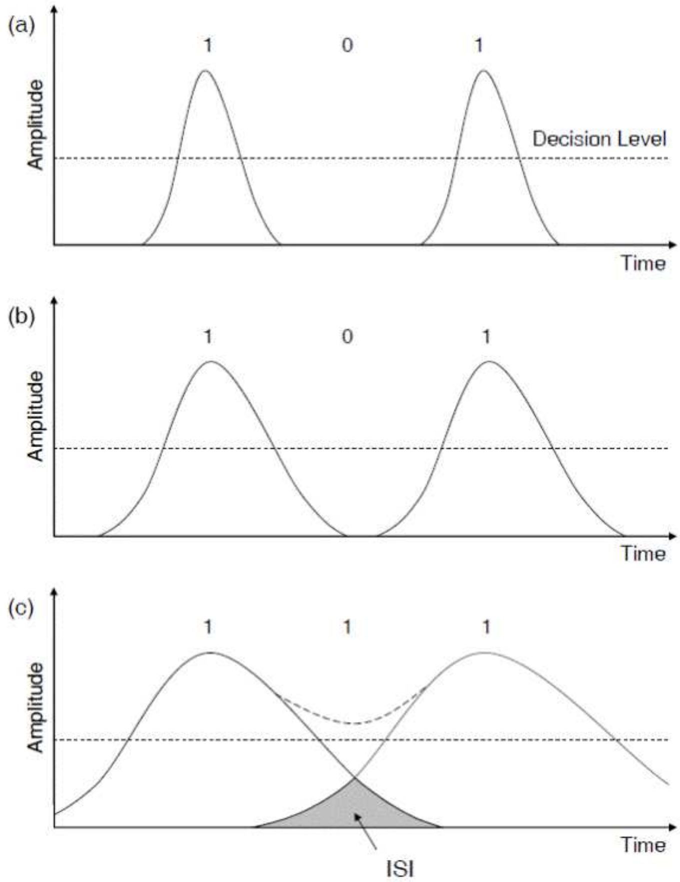

Figure 6 – Pulse spreading of a digital (101) bit streams during the propagation in a multimode fiber, (a) at coupling into the fiber, (b) after length l_1, (c) after length $l_2 > l_1$. The latter case leads to a bit error caused by significant ISI.

Higher bandwidth correlates with lower ISI power penalty. Contrary to other reports [4,9], all our measurements show that this correlation is still the same in BIMMF. Our 40 Gb/s transmission experiments show that BIMMFs that pass the same DMD templates as MMF also exhibit similarly low bit error rates. We have repeated these experiments with CFP transceivers from different vendors and could not observe an onset of a BER shoulder in our BIMMFs. On the contrary, we have seen very good performances of the optical channels with positive power margins in practice, as illustrated in Figure 7. The green area represents good OM3 and OM4 performance. As the optical power is reduced (from right to left) the BER increases.

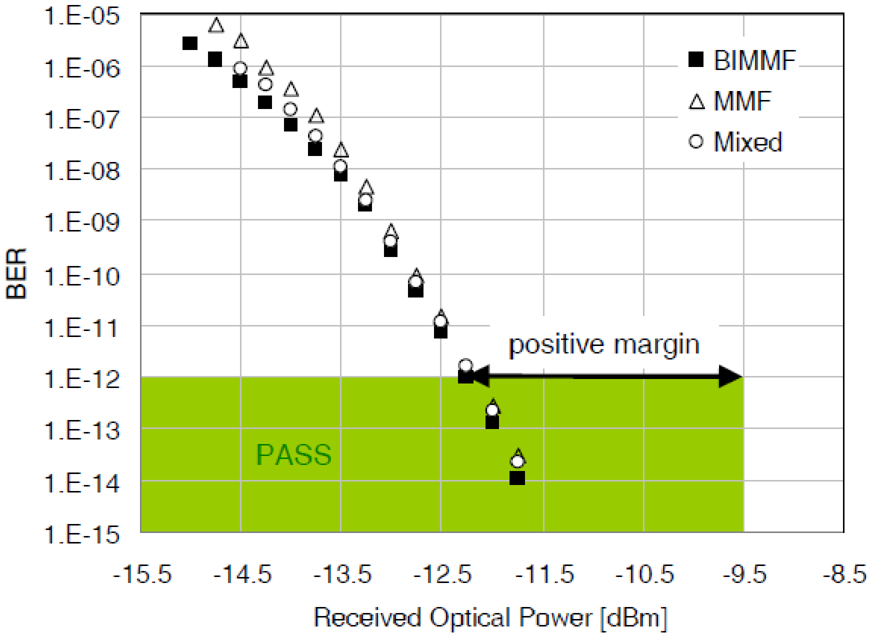

Figure 7 – BER waterfall curves of 40GBASE-SR4 transmission over concatenated OM4 cables of differing configuration with a total length of 150 m. The graph shows results for channels made of four BIMMF cables, four MMF cables and a channel made of intermated BIMMF and MMF cables.

Analysis of the data shows that all cases, namely either pure BIMMF, pure MMF and mixed BIMMF/MMF channels in various configurations, support 40 Gb/s data transmission for 150 meters and even more [12]. Figure 7 shows that for the 150 meters length, a bit error rate of 10^{-12} was measured at a receiver power of about -12.25 dBm. The requirement for measured receiver power is not to exceed a minimum specified optical power of -9.5 dBm. Thus, all measured configurations pass the IEEE 802.3ba Physical Medium Dependent (PMD) sub-layer requirements [1], provided that the transmitter and receiver in the system are conforming the specifications.

It was also claimed that the low-index trench around the fiber core would lead to the propagation of light in the highest-order modes which leads to a bandwidth degradation and an increase in the ISI power penalty [4,9]. In order to test this, BIMMF and MMF channels with three connections and total lengths of 550 m were investigated. Again, this test was carried out with commercially available trans-ceivers. The results are shown in the BER waterfall curves in Figure 8. It is obvious that BIMMF ca-bles perform as good as conventional MMF cables since both waterfall curves exhibit the same power penalties, i.e. the curves are basically lying on top of one another.

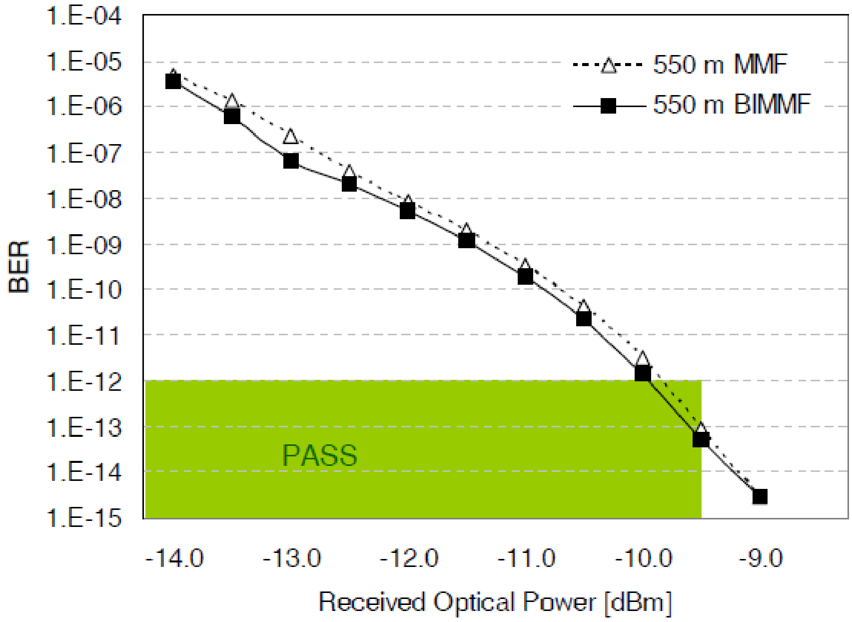

Figure 8– BER waterfall curves of 40GBASE-SR4 transmission over concatenated OM4 cables with a total length of 550 m. The graph shows results for channels made of only BIMMF or MMF cables.

To evaluate the transmission performance of BIMMF in comparison to MMF, eye diagrams were investigated for different transmission distances. Figure 9 shows measured eye diagrams for 150 and 550 meters for both fiber types. In all cases, clear opened eyes were measured which documents the high bandwidth that both BIMMF and MMF OM4 fiber exhibit.

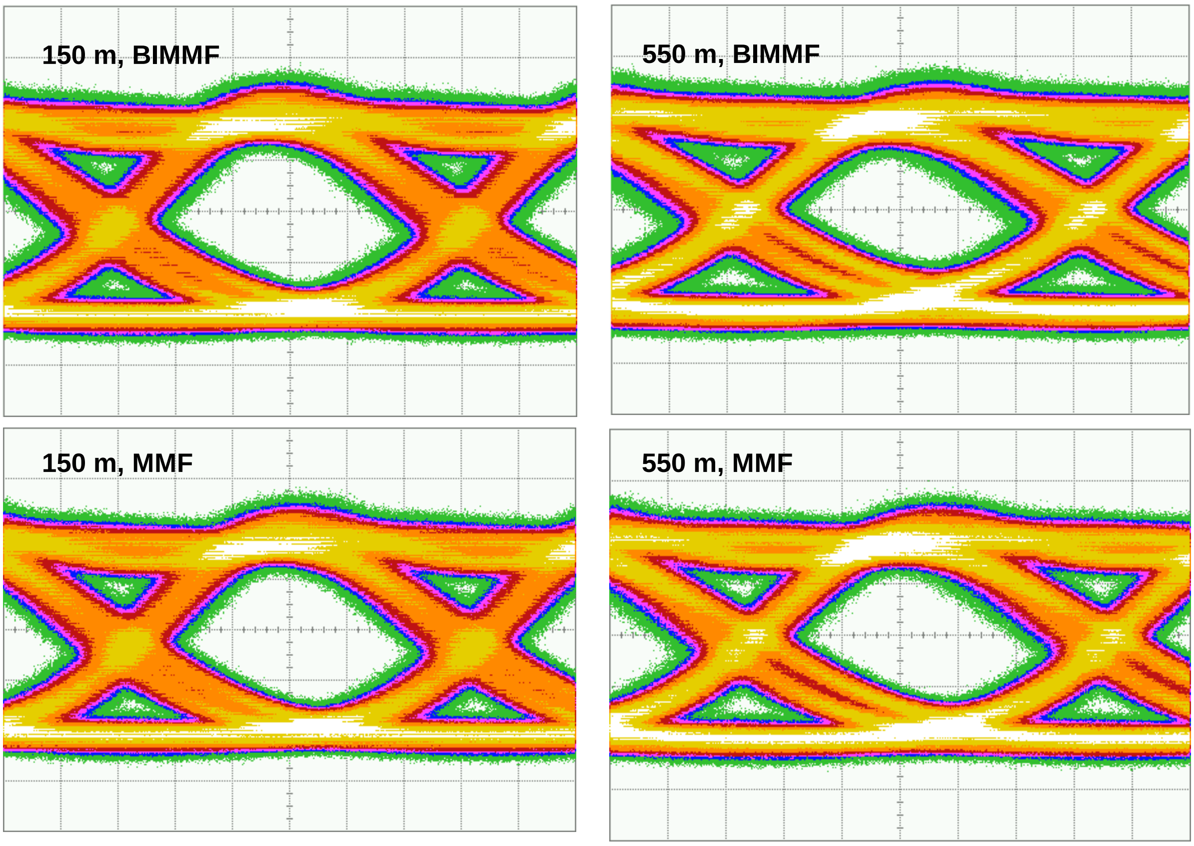

Figure 9 – Eye diagrams of commercial CFP transceiver in BIMMF and MMF configurations for two channel lengths. All diagrams are recorded at -9.5 dBm receiver power.

Rebuttal #4

From all measurements conducted during our investigations we can state that, provided a standard conform transceiver is employed, BIMMF has no negative impact on the system performance. It does not lead to higher modal dispersion and therefore neither results in larger power penalties compared to MMF nor in a BER shoulder.

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