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Intrinsic attenuation in multi-mode fiber interconnects

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Abstract

The ever decreasing limits imposed on allowable attenuation due to optical interconnects in multi-mode fiber optic networks has prompted the development of harmonized and improved measurement methods. Standardization committees have recently agreed to prescribe the launch conditions known as encircled flux (EF). Regardless of the measurement method, fiber intrinsic attenuation effects are often attributed to the performance of the connectors, in that they become crucial in terms of the minimum achievable attenuation. In the development of the launch, the core diameter has always been identified as an important parameter. However, according to geometrical optics based modeling presented in this paper, the numerical aperture is identified to be at least as important. Tight tolerances on intrinsic fiber parameters have become ever more important for the development of reference-grade connectors as well as of future high-performance multi-mode fiber connectors.

Keywords: Multi-mode fiber, core diameter, numerical aperture, encircled flux, geometrical optics, connectors.

1. Introduction

The ever increasing demand for higher bandwidth in multi-mode fiber networks constrains the allowable attenuation due to optical interconnects. To meet that demand, state-of-the-art fast light sources typically consume more power, while the photodetector needs to become smaller which reduces the coupling efficiency. In Figure 1, this decrease in the maximum allowed power budget is shown as function of increasing channel bandwidth for IEEE 802.3 standards [1].

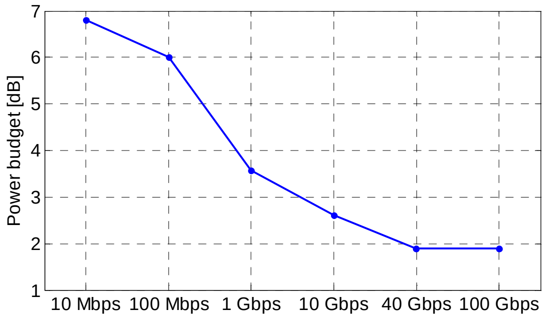

Figure 1. The maximum allowed power budget decreases with increasing channel bandwidth standards

In order to meet the power budget, the attenuation in optical interconnects should be reduced as much as possible. This becomes even more urgent as optical networks grow in size and complexity, which drives the need for an increased number of consecutive interconnects along a link. From a connector perspective, the biggest contributor to attenuation is the misalignment of the fiber optical axis with respect to the circumference of the ferrule which holds the fiber. Prior to making a connection, the ferrules of the two connectors are aligned in a coupler [2]. The eccentricities effectively result in a lateral misalignment of the two fiber cores, thus contributing to the attenuation. Over the years, connectors have not only been improved by reducing the fiber misalignment, also the connector end-face geometry has been prescribed in standards known as the optical interface [5]. However, the attenuation is not fully determined by the design of the connector. Given that fiber-intrinsic attenuation effects are often attributed to the performance of the connector, the minimum attainable attenuation also depends on the fiber geometry governed by the refractive index profile [3]. As such, subtle differences in fiber geometry across a fiber junction will contribute to the attenuation.

In practice, the attenuation of a particular interconnect is determined by measuring the difference in optical output power prior to, and after connecting the fiber under test (FUT). The absorption losses of the FUT are considered negligible for short-length fibers. Although this describes a straightforward measurement, it is well understood that the optical launch has significant impact on the outcome of the measurement [6]. For example, when low-order modal fields are dominantly present as a result of an under-filled launch (UFL), the outcome of the attenuation measurement will be optimistic as compared to when an over-filled launch is applied to the same interconnect. In the latter case, high-order modes are prone to leakage due to fiber bends and coupling losses, that the outcome may be pessimistic compared to the typical application, when VCSELs are employed. To quantify the launch, one may determine the coupled power ratio (CPR), which defines the ratio of two scalar measurements: the total optical output power before adding a FUT, and the power that would couple into a single-mode FUT. The ratio is then considered indicative for the presence of low-order modes compared to the high-order modes. Unfortunately, CPR does not accurately characterize the launch. To improve and harmonize the measurement method of multi-mode interconnects, standardization committees like the IEC [4][5][6], ISO/IEC [7], TIA [8], CENELEC [9], and JIS have recently developed and agreed upon a specific UFL known as the encircled flux (EF) launch condition for attenuation measurements. It prescribes targets on the near-field pattern in the reference fiber for the sake of repeatable and reproducible measurements [6]. This metrology is a significant improvement over CPR, because it incorporates the entire near-field pattern. In order to indicate the performance of a single connector, it may be measured against a reference-grade connector, which is defined in the standard as well [5].

From a theoretical point of view, fiber coupling simulations should be based on electromagnetic field computations, involving mode-matching techniques as a means to quantify the attenuation. Given that standard multi-mode fibers may support several hundreds of modes, it is a time-consuming task to compute the coupling attenuation for a large number of fiber junctions with subtle deviations in the refractive index profile. Hence, one often resorts to models based on geometrical optics (GO). We have used such a GO model to evaluate the performance of multi-mode fiber interconnects. The advantage of this approach is that a large number of couplings can be evaluated very rapidly. We have developed dedicated code that allows us to determine ray launch distributions that satisfy the EF targets, even for variations of the core diameter (CD) and numerical aperture (NA) about nominal values. By applying the launch on a large number of receiving fiber configurations, we modeled the attenuation with respect to core-diameter mismatch, NA mismatch and lateral misalignment. As such, we obtained requirements on intrinsic fiber parameters, which should subsequently enable us to manufacture reference-grade connectors. While the NA has not been incorporated explicitly in the development of EF, it turns out that NA mismatch plays at least as important a role in the coupling attenuation. Hence, tight tolerances on intrinsic fiber parameters have become even more important for the development of future multi-mode fiber connectors.

2. Geometrical optics approach

To model the fiber, we assume that the refractive index profile of the multi-mode fiber only depends on the radial direction r. Throughout this paper, the cross-section of the fiber is considered as the transverse plane, and is oriented perpendicular to the longitudinal axis, or optical axis, which is aligned with the z-axis. We assume that the refractive index profile is described by

$$n(r)=\begin{cases} n_{\text{core}}\sqrt{1-2\Delta\left(\dfrac{r}{R}\right)^{\alpha}} & \text{for } r<R \\ n_{\text{cladding}} & \text{for } r\geq R \end{cases}, \tag{1}$$

where n_{core} and n_{cladding} describe the core- and cladding refractive index respectively. The core radius is denoted by R and we assume that the power coefficient $\alpha = 2$. Further,

$$\Delta=\frac{n_{\text{core}}^2-n_{\text{cladding}}^2}{2n_{\text{core}}^2}, \tag{2}$$

so that the numerical aperture (NA) given by

$$NA=\sqrt{n_{\text{core}}^2-n_{\text{cladding}}^2}=n_{\text{core}}\sqrt{2\Delta}. \tag{3}$$

The cladding is typically pure silica, with an index of refraction $n_{\text{cladding}} = 1.452$ at the wavelength $\lambda = 850$ nm. A typical multi-mode fiber has a core radius R = 25 µm, and $NA = 0.2$ [3]. With the cladding refractive index chosen fixed, the NA is determined by the core refractive index in Eq. (3).

The refractive index profile of two multi-mode fibers as described by Eq. (1) may be different due to variations on CD and NA, so that an interconnect between the two will exhibit intrinsic attenuation. Such junctions have already been modeled using modal electromagnetic fields that are associated to a similar refractive index profile as in Eq. (1) by the IEC [6]. In fact, they used an unbounded refractive index profile. Moreover, the attenuations due to various receiving fiber geometries have also been evaluated. Because typical multi-mode fibers may support several hundreds of modes, studying large numbers of different fiber junctions is a time-consuming task. Particularly, including variations in the transmitting fiber requires that the modal amplitudes be recomputed in order to assure the launch is EF compliant. So for each configuration, the modal fields on either side of the junction need to be evaluated. Then, the contribution of each mode to the launch needs to be redetermined prior to solving the reflection-transmission problem. To overcome that, we have taken a geometrical optics (GO) approach to describe the field in the transmitting fiber that ensures EF compliance. By tracing the rays, we may determine the power P_r carried by the rays that are considered guided in the receiving fiber, relative to the power P_t in the transmitting fiber in less then a second. The attenuation follows from

$$\eta[\text{dB}]=-10\log_{10}\left(P_r/P_t\right). \tag{4}$$

In order to compare the GO model with the work that the IEC has already performed, consider two typical multi-mode fibers with CD=50 µm and NA=0.2 and the attenuation versus lateral misalignment in Figure 2. The results agree remarkably well, given the fundamentally different approach and the slightly different refractive index profile. For example, high-order modal electromagnetic fields typically have a tail extending in the cladding region, a region that cannot be described with real-ray GO, but instead requires complex rays as an extension to GO [10].

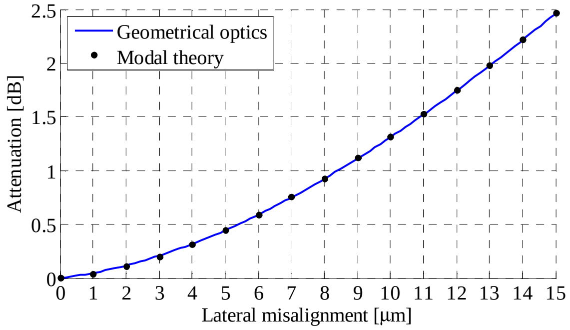

Figure 2. The attenuation versus lateral misalignment for a typical multi-mode fiber interconnect

In order to gain more confidence in the GO model, we also compared four models incorporating CD mismatches and NA mismatches with respect to a transmitting fiber with CD=50 µm and NA=0.2 as shown in Figure 3. The core diameter CDr and numerical aperture NAr of the receiving fiber are specified in the legend. Again, we observe good agreement between the two approaches.

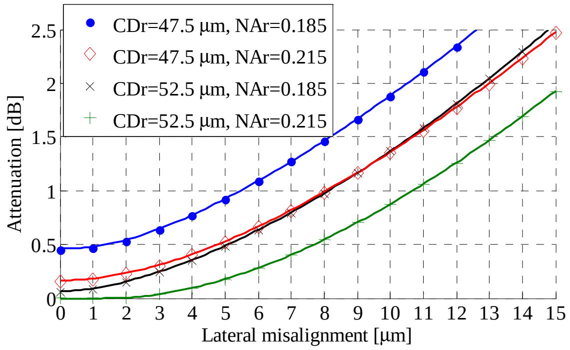

Figure 3. The attenuation versus lateral misalignment for various multi-mode fiber interconnects

Based on these results, one may expect that there are configurations which yield up to 0.5 dB of attenuation, despite ideal alignment. This means that such a fiber specification definitely does not permit the desired low attenuation for the reference-grade connectors to be achieved. We would also like to point out that other effects, like core non-circularity and alpha-profile mismatch will also affect the attenuation. With aid of GO, these effects may also be readily analyzed.

3. Analysis of subtle parameter variations

Before we proceed to determine sensible tolerances on fiber geometry parameters that would enable the manufacturing of reference-grade connectors, consider a measurement capability comparison on core diameter measurement performed several decades ago [11]. This study showed an intralaboratory standard deviation of 0.5 µm, and an interlaboratory agreement within 1 µm was achieved. Similar experiments have recently been conducted by the IEC on an industry level [12], where we contributed as a participant. Moreover, five years before, we also hosted a similar experiment [13]. Although three decades have passed, these studies did not show any significant improvements in measurement capability. From an industry perspective, it seems difficult to measure the nominal value and an adequately tight tolerance. The fiber geometry standard prescribes many aspects of multi-mode fibers, such as mechanical, transmission and environmental requirements, but also dimensional requirements including CD and NA [3]. Regardless of the well-known bandwidth performance classifications like OM2, OM3 and OM4, the tolerances on the dimensional aspects have not been tightened. In fact, the CD and NA are specified by nominal values of 50 µm and 0.2, and tolerances 2.5 µm and 0.015 respectively. To investigate the influence of the respective tolerances, we have conducted a series of experiments for pairs of fibers with core diameters that are uniformly distributed within a sequence of set variation bounds (or limits) indicated on the horizontal axis (associated with the black dashed curve) in Figure 4, while keeping the numerical apertures fixed at the nominal value. Likewise, while keeping the core diameters fixed at the nominal value, the worst case attenuation due to variations of imposed bounds on the numerical apertures are shown on the second horizontal axis (associated with the red solid curve). The horizontal axes are chosen such that each division corresponds to 1% of the nominal value. It readily indicates that the attenuation is much more sensitive to variations in NA than in CD.

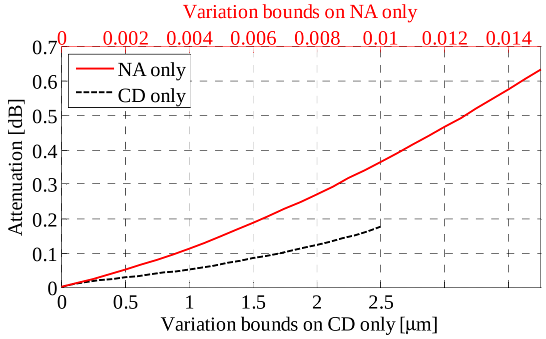

Figure 4. The attenuation when variation bounds on CD and NA are considered independently

Remarkably, the biggest contributor to attenuation is currently allowed to have the largest tolerance. Upon incorporating both tolerances simultaneously in our model, the attenuation becomes much larger, and can be as high as 1.2 dB for the worst case configuration. In view of the development of the EF metrology, it now seems incomprehensible that the impact of NA has not been recognized, and has been incorporated only implicitly. One can now imagine that the worst case attenuation rapidly increases to levels that are far too large in view of the available power budget. However, we would like to stress that such large attenuation measurements are not commonly seen in practice. To assess the performance of an arbitrary connector, the attenuation measurement should be conducted with respect to a reference-grade connector. A reference-grade connector permits good alignment due to a negligible eccentricity, and should have an attenuation as low as 0.1 dB when measured against other reference-grade connectors [5]. In view of Figure 4, the choice of the fiber in the reference-grade connector will have a profound impact on the classification of large numbers of connectors. Moreover, to assure that reference-grade to reference-grade connections keep below 0.1 dB, the tolerances should be tightened, and measurement methods of fiber geometry improved drastically.

4. Towards reference-grade connectors

The tolerances in the examples shown above are too loose for reference fibers. To satisfy the required low attenuation values, we have evaluated the worst case attenuation as function of combined variation bounds on CD and NA in Figure 5. For example, upon considering all possible configurations where the core diameters of both the transmitting and receiving fiber satisfy 50 ± 0.5 µm (highlighted in the figure below), we determined that the worst case attenuation associated with a variation bounds on the NA of ± 0.0025 gives a worst case attenuation of 0.1 dB. The tolerance configurations that have a worst case attenuation of 0.1 dB are subsequently listed in Table 1.

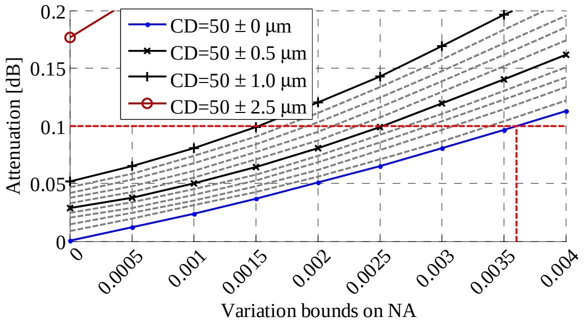

Figure 5. The maximum attenuation associated with variation bounds on CD and NA

The figure above also shows that the variation limits may certainly not be treated independently. For example, consider the case when the maximum allowed variation on CD and NA are ± 1.0 µm and ± 0.004 respectively, then upon considering all possible connections, the maximum attainable attenuation would exceed 0.2 dB, rather than get to 0.16 dB upon considering them independently from Figure 4. For reference fibers in reference-grade connectors, a tight tolerance similar to configurations listed in Table 1 should be used, albeit even tighter to allow for a finite eccentricity. We may then proceed to determine the attenuation distribution for reference-to-reference connections. We argue that since the tolerances should be so tight, the fibers may need to be preselected from a normal distribution with a relatively large standard deviation, so that the eventual collection of reference-grade fibers may subsequently be considered uniformly distributed in CD and NA.

Table 1. Fiber geometry specifications which result in a worst case attenuation of 0.1 dB

CD [μm]	NA
50 ± 0.0	0.2 ± 0.0036
50 ± 0.1	0.2 ± 0.0034
50 ± 0.2	0.2 ± 0.0031
50 ± 0.3	0.2 ± 0.0029
50 ± 0.4	0.2 ± 0.0027
50 ± 0.5	0.2 ± 0.0025
50 ± 0.6	0.2 ± 0.0023
50 ± 0.7	0.2 ± 0.0021
50 ± 0.8	0.2 ± 0.0019
50 ± 0.9	0.2 ± 0.0017
50 ± 1.0	0.2 ± 0.0015

Consider the following reference-grade connector specification, CD 50 ± 0.5 μm, NA 0.2 ± 0.0020 and eccentricity ≤ 0.45 μm, which we will refer to as *ref1*. It has a worst case attenuation of 0.1 dB, which we have verified by performing 30,000 simulations. The associated cumulative distribution function has a long tail as shown in Figure 6, so that 97% of the reference-to-reference connections perform better than 0.052 dB. Therefore, we also evaluated a less restrictive distribution *ref2* with the specification CD 50 ± 0.6 μm, NA 0.2 ± 0.0025 and eccentricity ≤ 1.0 μm. This assures that the worst-case attenuation is 0.18 dB, and that 97% of the connections perform better than 0.1 dB.

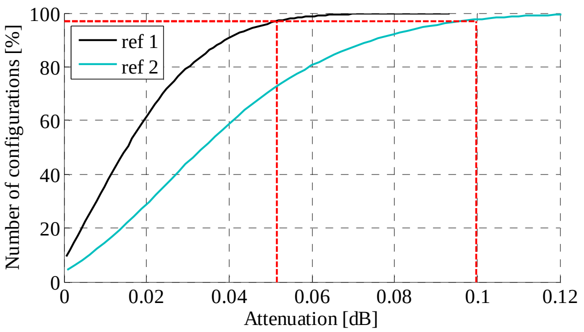

Figure 6. The cumulative distribution function of the attenuation of two connector specifications

Let us consider four arbitrary connectors, with specifications given in Table 2. We are interested in the attainable attenuations if these would be measured against large numbers of reference connectors from the two distributions. The CD and NA of these four connectors are below the nominal values, so that the attenuation will be larger than zero. The specification of the first reference distribution was chosen particularly tight, to demonstrate the effects of measuring an arbitrary connector. The attenuation distribution measured with arbitrary reference connectors *ref1* are shown in Figure 7. The attenuation is given as function of lateral misalignment as well as frequency of occurrence for each of the four connectors, which is effectively Gaussian. The minimum and maximum attenuation, as well as the mean and standard deviation of the approximated Gaussian distributions are listed in Table 3. Upon considering connector 1, the variation in attenuation is mainly caused by mismatches in CD and NA with respect to all reference connectors. The variation is very close to 0.1 dB, because the connector was chosen to have a particularly small eccentricity. Obviously, the variation in the possible misalignment also contributes to the attenuation distribution as seen for connector 4. So to accurately measure the attenuation of a connector with a large eccentricity, the alignment of the reference fiber in the reference connector becomes even more important.

Table 2. The fiber geometry specification for four arbitrary connectors under test

Connector	CD [μm]	NA	Eccentricity [μm]
1	49.68	0.1916	0.30
2	48.29	0.1877	1.06
3	49.03	0.1890	1.41
4	48.29	0.1877	3.00

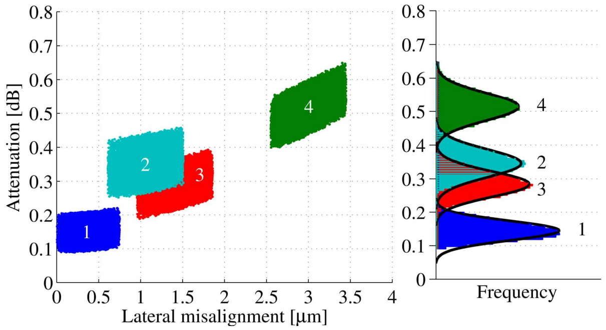

Figure 7. Attenuation distributions obtained with reference connectors defined by *ref1*.

To exaggerate the effect of lateral misalignment, consider the same four connectors evaluated by connectors from the distribution characterized by *ref2* in Figure 8. The difference between connectors 1 and 4 becomes even more significant, evidenced by the increase in the standard deviation.

Table 3. Typical attenuation values obtained for two reference connector definitions.

	Ref 1				Ref 2			
	Mean	Std dev	Min	Max	Mean	Std dev	Min	Max
1	0.15	0.03	0.09	0.22	0.15	0.04	0.08	0.27
2	0.35	0.04	0.25	0.46	0.35	0.05	0.23	0.52
3	0.29	0.04	0.19	0.39	0.29	0.05	0.16	0.46
4	0.52	0.04	0.40	0.65	0.52	0.06	0.33	0.73

Hence, to attain an overall low variation in measured attenuation, a reference connector should have negligible eccentricities and as little variation in fiber geometry as possible. In the evaluation of these hypothetical cases, we did not include core non-circularities, or alpha-profile mismatches, but more importantly, we assumed that the variations were about nominal values. The latter assumption has serious implications for the mean attenuation evaluated for arbitrary connectors, because the CD mismatch and NA mismatch with respect to the reference connector are reflected in the measurements. With the current definition, the requirements for reference connectors may be satisfied, regardless of the nominal core diameter and NA of the fiber used, which is not desirable. If nominal values are not explicitly standardized, one can imagine that many connectors may deceitfully be evaluated as high performance connectors when the reference fiber is in fact below nominal, or vice versa. It seems therefore much more sensible to have a well-defined fiber in a well-defined reference connector, however, that urgently requires the ability to measure fiber geometries much more accurately than is possible with currently available equipment or measurement techniques.

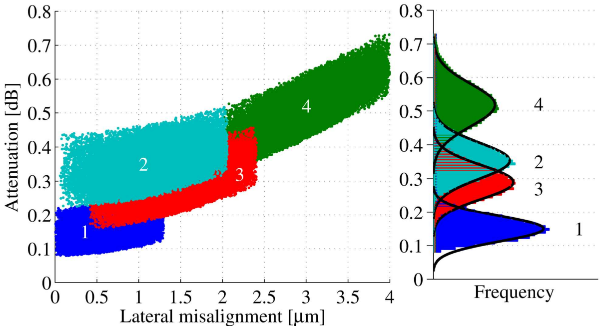

Figure 8. Attenuation distributions obtained with connectors defined by *ref2*.

5. Conclusions

Given that fiber-intrinsic attenuation effects are often attributed to the performance of the connector, the minimum attainable attenuation becomes dependent on the fiber geometry governed by the refractive index profile. We have demonstrated with aid of geometrical optics modeling, that subtle variations in the refractive index profile of two standard multi-mode fibers in a connection has huge implications on the attenuation. In particular, we have shown that the attenuation is more sensitive to variations in the NA than it is to the CD. Unfortunately, the former suffers from the largest tolerance in standardized fiber geometry specifications, and we showed that the attenuation may exceed 0.6 dB, while the latter may contribute up to 0.2 dB when the two are considered independently. Upon combining the two parameters, the attenuation becomes much larger, and can be as high as 1.2 dB for a worst-case configuration. The attainable attenuation exceeds the available power budget for state-of-the-art fast communication systems. Thus far, the influence of the intrinsic attenuation due to CD and NA mismatches has been ignored by the IEC, for example in the development of the EF launch. In order to meet the specification for reference-grade connectors, the tolerances should be tightened. We demonstrated the measurement of four randomly chosen connectors by reference-grade connectors from two distributions. Reference connectors should have negligible eccentricities, but should also be have nominal values of CD and NA. Unfortunately, measurement capabilities for CD measurements have not improved over the last three decades. We have demonstrated that measurement capabilities should be improved urgently, in order to meet the requirements of the newly developed IEEE applications (i.e. 40 Gbps and 100 Gbps), and for sake of the advance of high-performance multi-mode fiber optical interconnects.

6. Acknowledgments

The authors thank Frans van Geijn and Dave Walker of TE Connectivity, and Gerard Kuyt of Prysmian Group for providing information on standards.

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8. Pictures of Authors

Sander J. Floris was born in 1984 in Drachten, The Netherlands. He received his M.Sc. degree (cum laude) in electrical engineering from Eindhoven University of Technology, Eindhoven, The Netherlands, in 2011. He then joined the fiber optic development group of TE Connectivity, Enterprise Networks. He is working towards a Ph.D. degree in the Electromagnetics Group of the department of Electrical Engineering at Eindhoven University of Technology. His current research interests include numerical and physical aspects of high-frequency electromagnetic fields and fiber optics.

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Ton Bolhaar started to work for AMP in 1980 as BSc in Electrical Engineering. Ever since, he held several different positions within the company all related to fiber optics. Currently, he is manager of the fiber optic development group of Enterprise Networks. He is active in standardization in IEC, CENELEC and ISO/IEC SC-25. In particular, he is convenor of IEC SC86B WG4 Fibre Optic test and measurement standards, chair of the Dutch committee NEC 86B and Dutch committee for structured cabling NEC 38125.