Small Core Fiber Optic Connectors Performance Model

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The effect of lateral offset and angular misalignment in optical fibre connectors are analyzed as a function of fiber core diameter and wavelength. Model calculations are then compared to experimental results and discussed in relation with the used fibre type

1 Introduction

The vast majority of optical fiber produced today is used for telecommunications. The telecommunications industry has promulgated standardized measurement methods and performance classes for products operating in the near-infrared (NIR) spectrum, specifically at the 1310nm and 1530-1625nm wavelengths.

Because it has shown to offer numerous advantages over free-space optics, fiber technology has found application in a number of new areas, mostly in sensing systems in the industrial, biological, chemical analysis, security, military, space and R&D fields.

Many of these sensing systems utilize small-core fiber optimized for operation in the visible and near-ultraviolet spectrum (800–350nm). This poses new challenges for the fiber optic connectors used therein. Achieving repeatable, low-loss connections requires enhanced levels of precision and accuracy from these components. This article serves to describe the underlying mechanisms that affect the insertion loss (IL) of a fiber optic connection, and presents a model to describe connector performance in smaller-core fiber.

Experimental results corroborating the model are presented.

2 Measurement standards and model for the Insertion Loss (IL)

2.1 Measurement standards

The insertion loss (IL) of a fiber optic connector is measured as defined in IEC 61300[1] and is calculated as follows:

$$IL = -10 \cdot \log\left(\frac{P_{DUT}}{P_{ref}}\right)$$

Eq. 1

Where: P_{DUT} = transmitted power of the device under test (DUT)

P_{ref} = reference power, without DUT

Power: [P], in mW,

Insertion loss: [IL], in dB

IL measurements of individual connectors are conducted per IEC 61300-3-4[2], Method B. The sample assembly's length should be such that the attenuation contributions from the fiber can be ignored.

Statistical IL values are tabulated per IEC 61300-3-34[1], randomly mated (ie. every connector against every other connector).

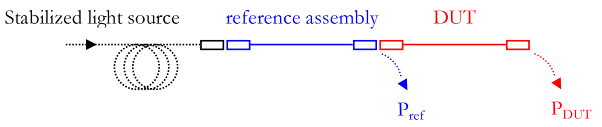


Fig. 1 Schematic diagram of IL measurement procedure

2.2 Model

The IL of a physical contact (PC) connector is primarily determined by fiber parameters (Mode Field Diameter (MFD) and the index of refraction of the core (n_0)), by the wavelength (λ), lateral (d) and angular(θ) alignment errors between the mating fiber cores.

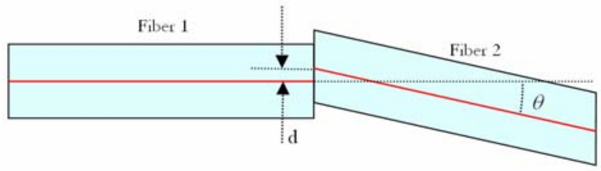


Fig. 2 Definition of lateral (d) and angular(θ) alignment error between the cores (red line) of two mating optical fibers

D. Markuse showed for mechanical splices[3] that IL can be calculated by Eq. 2. This method has been used,verified, and adopted in various international standards such as IEC 61755[1] .

$$IL = -10 \cdot \left(\frac{(2\omega_2\omega_1)^2}{(\omega_2^2+\omega_1^2)^2} \cdot \exp\left(\frac{-2d^2}{\omega_2^2+\omega_1^2} - 2\pi^2 \cdot \frac{n_0^2\omega_2\omega_1}{\lambda^2(\omega_2^2+\omega_1^2)} \cdot \sin^2(\theta) \right) \right)$$

Eq. 2

Where: λ = Wavelength of light in a vacuum

n_o = Core index of refraction

ω_1 = Mode field radius of launch fiber

ω_2 = Mode field radius of receiving fiber

From Eq. 2, one can derived a simpler form using the same fiber (i.e. $\omega_1=\omega_2$) on each side.

$$IL = K1 \cdot d^2 + K2 \cdot \theta_{\deg}^2$$

Eq. 3

By understanding K1 and K2, one can deduce their influence on small core fibers.

The lateral offset coefficient, K1, increases with the square of decreasing mode field diameter.

The angular misalignment coefficient, K2, remain stable with diminishing MFD. This is shown in Fig. 3.

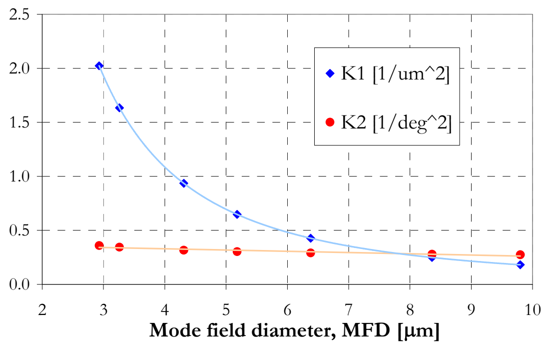


Fig. 3 Variation of the lateral offset K1 coefficient (blue) and the angular offset K2 coefficient (red)

From Fig. 3, we can see that for VIS-NUV wavelengths, lateral offset has a pronounced impact on IL, and this parameter requires close attention when connectors are terminated.

3 Experimental Investigation

For this study, a series of connectors were terminated on single mode (SM) and polarization-maintaining (PM) fiber optimized for the 400-800nm wavelength range with MFD ranging from 3µm to 5µm. The connectors featured 0° physical contact (PC) endface polishes.

The connectors further featured a two-component ferrule construction, consisting of ceramic (ZrO_2) outer ferrules and titanium inserts. Ferrules of this construction are standardized under IEC 61755[4] as optical interfaces for telecommunications.

The termination process, known as Active Core Alignment[5] **(ACA)**, included core eccentricity and exit angle measurements, allowing comparison of the experimental data to the model . Relevant process parameters included:

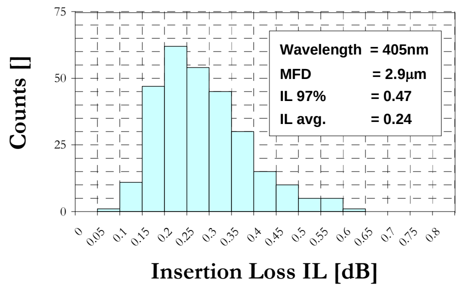
- Tight ferule tolerance < 0.2µm ($2.500\,^{-0.0008}_{-0.001}$)
- Eccentricity < 0.125µm
- Exit angle < 0.4°

Using these parameters, IL values ≤ 0.1 dB are routinely achieved in production for telecommunications-grade connectors.

3.1 Insertion loss (IL)

A series of patchcords with fibers for 405nm (MFD=2.9µm), 532nm (MFD=3.5µm), 630nm (MFD=4.2µm) and 780nm (MFD=4.6µm) were built using the above-mentioned process.

IL measurements on these patchcords per IEC 61300-3-4, Method B showed good agreement with the model, as shown in Fig. 4.



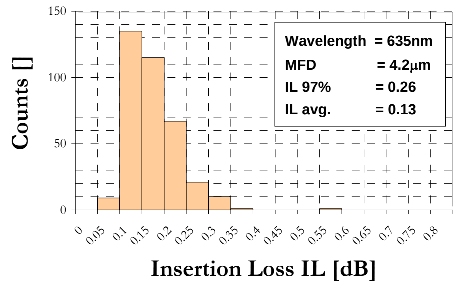


Fig. 4 Histogram for 405nm and 635nm of IL random

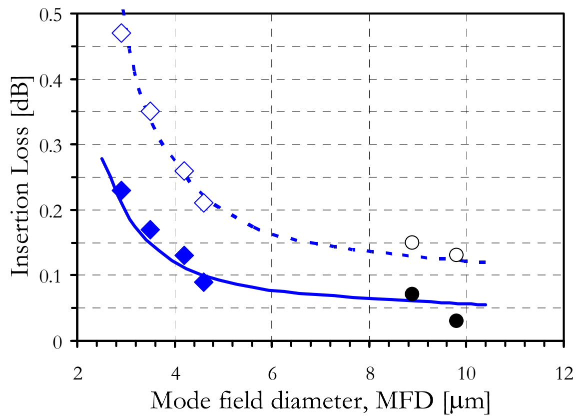


Fig. 5 IL, experimental values vs. simulation, for single mode connectors.

(Simulation using Eq. 3 for 1000 connector pairs with varying amounts of concentricity and lateral offset derived from production data, at selected wavelengths.

Solid line represents average values for randomly-mated pairs, broken line represents the 97% confidence level.

◆● = Average IL from experimental results

◇○ = 97% confidence level from experimental results

The values at 1310nm and 1550nm (●○) reported were presented at a Cenelec meeting in Krakow in May 2007.)

The results presented here show good correspondance from model to experimental data..

4 Conclusion

The effects of lateral and angular alignment mismatches between mating cores in fiber optic connectors is greatly influenced by the mode field diameter and experimental data was shown to confirm validity of the model used for standard telecom NIR fibers.

It was also shown that for small core fiber, lateral offsets are the primary source of connector insertion loss (IL).

Already thoroughly proven in the traditional telecommunications spectral bands (1310nm and 1530–1625nm), **Active Core Alignment** is powerful tools for the production of high-precision connectors to handle the demands of the visible and near-ultraviolet spectrum.

5 Annex

5.1 Equation reduction

$$IL = -10 \cdot \log\left(\frac{(2\omega_2\omega_1)^2}{(\omega_2^2+\omega_1^2)^2} \cdot \exp\left(\frac{-2 \cdot d^2}{\omega_2^2+\omega_1^2} - 2\pi^2 \cdot \frac{n_0^2}{\lambda^2} \frac{\omega_2^2\omega_1^2}{\omega_2^2+\omega_1^2} \sin^2(\theta) \right) \right),$$

$$\omega_1 = \omega_2 = \omega$$

$$IL = -10 \cdot \log\left(\underbrace{\frac{4\omega^2}{4\omega^2}}_{1} \cdot \exp\left(\frac{-d^2}{\omega^2} - \pi^2 \cdot \frac{n_0^2 \cdot \omega^2}{\lambda^2} \sin^2(\theta) \right) \right), \quad \log(a) = \frac{\ln(a)}{\ln(10)}$$

$$IL = -10 \cdot \frac{\ln\left(\exp\left(\frac{-d^2}{\omega^2} - \pi^2 \cdot \frac{n_0^2 \cdot \omega^2}{\lambda^2} \sin^2(\theta) \right) \right)}{\ln(10)}$$

$$IL = \frac{-10}{\ln(10)} \left(\frac{-d^2}{\omega^2} - \pi^2 \cdot \frac{n_0^2 \cdot \omega^2}{\lambda^2} \sin^2(\theta) \right), \quad \omega = MFR = MFD/2$$

$$IL = \underbrace{\frac{40}{MFD^2 \cdot \ln(10)}}_{K1} \cdot d^2 + \underbrace{\frac{2.5\pi^2 n_0^2 MFD^2}{\lambda^2 \ln(10)}}_{K2'} \cdot \sin^2(\theta)$$

$$IL = K1 \cdot d^2 + K2' \cdot \sin^2(\theta),$$

for small angles, we have $\sin^2(\theta_{rad}) = \theta_{rad}^2 = \theta_{\deg}^2 \cdot (\pi/180)^2$

$$\Leftrightarrow \qquad IL \cong K1 \cdot d^2 + K2 \cdot \theta_{\deg}^2,$$

$$K1 = \frac{40}{MFD^2 \cdot \ln(10)},$$

$$K2 = \frac{2.5\pi^2 n_0^2 MFD^2}{\lambda^2 \ln(10)} \cdot (\pi/180)^2$$

5.2 Various fiber parameters

Manufacturer	P/N	MFD	Wavelength	NA
OFS	CL980 14	9.4	1550	0.14
OFS	Allwave	10	1550	0.14
Nufern	UHNA3	4.1	1550	0.35
Nufern	UHNA1	4.8	1550	0.28
Nufern	980-HP	6.8	1550	0.2
Nufern	1550B-HP	9.5	1550	0.13
Corning	Clearcurve XB	9.8	1550	0.13
Corning	SMF-28e+	10.4	1550	0.12
Corning	Panda PM 1550	10.5	1550	0.09
OFS	Allwave	8.9	1310	0.14
Corning	Clearcurve XB	8.6	1310	0.13
Corning	SMF-28e+	9.2	1310	0.12
Corning	Panda PM 1300	9	1300	0.09
Nufern	1060-XP	6.2	1060	0.14
OFS	CL980 14	5.9	980	0.14
Nufern	980-HP	4.2	980	0.2
Nufern	1060-XP	5.9	980	0.14
Nufern	PM980-XP	6.6	980	0.13
Corning	Panda PM 980	6.6	980	0.09

Manufacturer	P/N	MFD	Wavelength	NA
Nufern	780-HP	5	850	0.13
Nufern	PM780-HP	5.3	850	0.12
Corning	Panda PM 850	5.5	850	0.09
OFS	CL 820 16	4.1	820	0.16
OFS	CL 780 11	5.4	780	0.11
OFS	CL 630 11	4.3	630	0.11
Nufern	S630-HP	4.2	630	0.12
Nufern	PM630-HP	4.5	630	0.12
Nufern	630-HP	4	630	0.13
Corning	Panda PM 630	4.5	630	0.09
Corning	RGB400	3.9	600	0.12
Nufern	PM460-HP	3.3	515	0.12
Nufern	405-HP	3.5	515	0.13
Nufern	460-HP	3.5	515	0.13
Corning	RGB400	3.2	500	0.12
Corning	Panda PM 480	4	480	0.09
Nufern	S460-HP	3.4	460	0.12
Corning	Panda PM 400	3.5	410	0.09
Nufern	S405-HP	2.9	405	0.12

5.3 References

[1] "*Fibre Optic Interconnecting Devices and Passive Components – Basic Test and Measurement Procedures*" ,IEC-61300 Standard Series

[2] http://www.diamond-fo.com/media/library/docs/TN001_IL_Measurement.pdf

[3] "*Loss Analysis of Single-Mode Fiber Splices*", D. Markuse, The Bell System Technical Journal, *56*, 1977, p. 703-718

[4] "*Fibre Optic Connector Optical Interface*", IEC-61755 Standard Series

[5] "*Active Alignment Process Reduces Fiber-Core Offset*", M. Graf, Laser Focus World, July 1996