

Low-Loss Intermateability of APC-MPO Connectors between Different Material Plugs: Statistical and Experimental Study

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Abstract

We propose the geometrical alignment model of the APC-MPO (Angled Physical Contact-Multi-fiber Push On) connector for accurate connection loss estimation from the plugs dimensions. Connection losses are estimated from offsets and angle errors calculated from the guide structure parameters, deformation of guide pins and holes caused by mating force. We propose a low-loss APC-MPO connector design with *Yoffset* in MT (Mechanically Transferable) ferrule for compensating y-direction eccentricities. We demonstrated the low-loss design between plugs with different materials and different guide hole diameters, and confirmed the effectiveness of the design by experiments and the Monte Carlo simulation. The two 12-Fiber single mode APC-MPO plugs with different materials and guide hole diameter difference of 0.45 [μm] had low connection losses of less than 0.25 [dB] for 97% value.

Keywords: alignment, APC, FTTH, guide hole, guide pin, high density Monte Carlo simulation, MPO, MT ferrule, multi-fiber connector.

1. Introduction

In FTTH field, it is necessary to connect a large count of optical fiber at many points. MPO connectors are the most demanded connector due to its multiple fiber connection capability in 10 times higher density than simplex connectors [1]-[7]. In Figure 1, the structure of APC-MPO connector is illustrated. Two multi-fiber plugs with angled end-faces are aligned by two guide pins, and connected by an adaptor. Since the end-face is angled in 8 degrees, higher than 60 dB return losses are obtained. In addition, the protruded fibers from the plug end-face enable physical contacts and low-loss connections. However, in order to introduce MPO connectorized cables in the FTTH networks, a low-loss intermateable specification is required for cable connections between different lots and different suppliers. Since the structure is more complex than simplex fiber connectors, up to now, even MT/MPO's connection offsets and tilts were not expressed by equations with connector dimension parameters. Therefore connection losses of different plug combinations were not clarified. Connector loss distribution performances between MPO plugs of different lots were investigated only by the connection loss measurements using actual assembled plugs. The core position in y-direction has a shift/eccentricity caused by the clearance between the guide pin and the guide hole. For low-loss connections among different lot plugs, this should be compensated. However, the relation between the connector loss performance and the parts specification was not clear. Moreover, the connection loss among different lots of plugs in the field was not predictable from plug parts data.

This paper reports,

(1) The condition to enable the low-loss intermateability performance for different lot connector plugs combinations consisted with different sizes and different materials.

(2) Connector loss estimating method to enables accurate loss estimations from the parts dimensional data before assembling.

The main purpose of this paper is, in order to enhance MPO connector mass introduction into FTTH large-scale cable systems, to clarify connector dimensional specifications for low-loss connections even among different lot connectors. Moreover, by establishing the connector loss estimating method from the parts dimensional data before assembling, we can predict connector loss performances among different lots connectors in the FTTH fields.

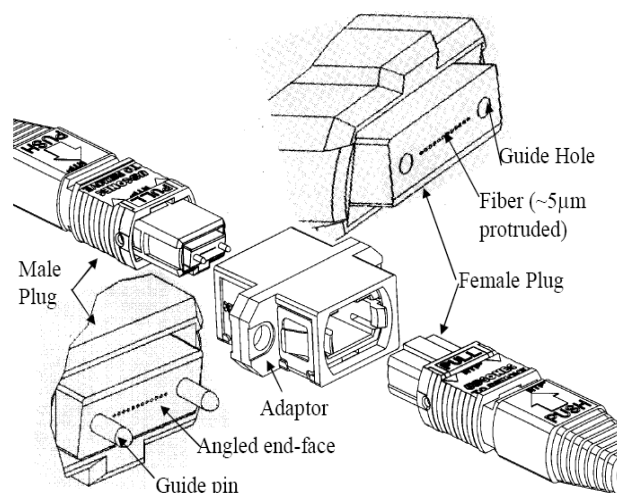


Figure 1. APC-MPO connector structure

2. Alignment structure of SM APC-MPO connector

SM optical fiber connector transmission efficiency T is expressed by (1) presented by Marcuse [8]. Where, ω_1 and ω_2 are a mode

$$T = \frac{2(\omega_2\omega_1)^2}{(\omega_2^2 + \omega_1^2)^2} \exp \left\{ \frac{-2d^2}{\omega_2^2 + \omega_1^2} - \frac{2(\pi n_0 \omega_2 \omega_1 \theta)^2}{\lambda^2 (\omega_2^2 + \omega_1^2)} \right\} \quad (1)$$

field radius for the in-coming and that of out-going fiber respectively. These values are specified by IEC international standard. And d is offset and θ is angle error between mated fibers. In the simulation in this report, we treat d , θ , ω_1 , and ω_2 as variables. We treat n_0 refractive index of the core center and λ wavelength of propagating light as constants. The propagation light wave length used in this report is 1310 [nm] which is the

most important in FTTH. The targeted optical fiber is the most common SM optical fiber specified as type B.1.3 in IEC International Standard 60793-2-50 Optical Fiber Specification.

2.1 MT ferrule alignment

Figure 1 illustrates two of APC-MPO connector plugs coupled by one adaptor. The male plug has two guide pins and the female plug has two guide holes. In each plug a MT ferrule is included. In MT ferrule, arrayed fibers and two guide holes are aligned with sub micron location accuracies. Each optical fiber is protruded slightly (1 to 5 μ m) from the end surface of the MT ferrule. The adaptor is keeping the plugs mating force to press the endfaces of the mated plugs in the axial directions with a specified pressure. By this mating force physical contact (PC) connections are maintained between mated fibers. Therefore, the connection losses are low due to no Fresnel reflections, and the return losses are high due to the endfaces polished in eight degree angle. Figure 2 shows the structure of MT ferrule endface in APC-MPO connector plug. MT ferrule has multiple fiber holes and two guide holes. The middle point of the line segment that connects the center of two guide holes is defined as the origin of coordinates. The x-y axis is defined as shown in Figure 2. Multiple fiber holes are arranged on x axis by 250 micron pitch. The core center position and the mode field Center (MFC) position are assumed to be corresponding.

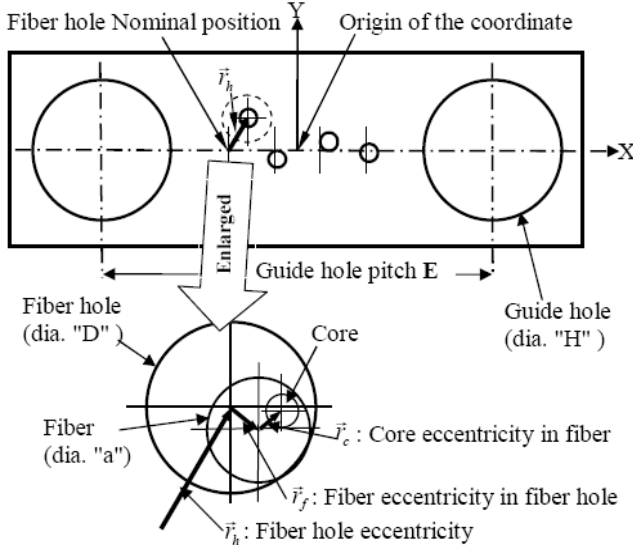


Figure 2. MT ferrule / plug endface. Co-ordinate for each core.

Now, let's describe MFC position of each fiber fixed in a MT ferrule. The eccentricity of the j th optical fiber insertion holes of the i th plug is assumed as $\vec{r}_{hji}(x_{hji}, y_{hji})$. The probability density function of this hole position is shown by a two dimensional Gaussian distribution.

$$p(x_{hji}) = \frac{1}{\sqrt{2\pi\sigma_{hji}}} \exp\left(-\frac{x_{hji}^2}{2\sigma_{hji}^2}\right),$$

$$p(y_{hji}) = \frac{1}{\sqrt{2\pi\sigma_{hji}}} \exp\left(-\frac{y_{hji}^2}{2\sigma_{hji}^2}\right). \quad (2)$$

The standard deviation of this distribution is defined as the 1/6 value of the range of the part dimension specification. The value outside the range is defined to be rejected. This definition is the same in quality controls of the parts manufacturing process. The optical fiber is inserted into the adhesive filled hole randomly, and the adhesive is cured. The center values of the optical fiber diameter and the hole diameter are defined to be D_0 and a_0 , and standard deviations are σ_D and σ_a respectively. Each probability density function $p(D_{ji})$ and $p(a_{ji})$ is shown by (3).

$$p(D_{ji}) = \frac{1}{\sqrt{2\pi\sigma_D}} \exp\left(-\frac{(D_{ji} - D_0)^2}{2\sigma_D^2}\right), \quad (3)$$

$$p(a_{ji}) = \frac{1}{\sqrt{2\pi\sigma_a}} \exp\left(-\frac{(a_{ji} - a_0)^2}{2\sigma_a^2}\right).$$

The eccentricity of the optical fiber in the hole $\vec{r}_{fji}(x_{fji}, y_{fji})$ is expressed by a two dimensional Gaussian distribution (4). Where, the probability density depends on the clearance between D and a , and standard deviation is expressed as $\sigma_{fji} = (D_{ji} - a_{ji})/6$ [9].

$$p(x_{fji}) = \frac{1}{\sqrt{2\pi\sigma_{fji}}} \exp\left(-\frac{x_{fji}^2}{2\sigma_{fji}^2}\right), \quad (4)$$

$$p(y_{fji}) = \frac{1}{\sqrt{2\pi\sigma_{fji}}} \exp\left(-\frac{y_{fji}^2}{2\sigma_{fji}^2}\right).$$

The probability density function of the fiber core center is expressed as (5).

$$p(x_{cji}) = \frac{1}{\sqrt{2\pi\sigma_{cji}}} \exp\left(-\frac{x_{cji}^2}{2\sigma_{cji}^2}\right), \quad (5)$$

$$p(y_{cji}) = \frac{1}{\sqrt{2\pi\sigma_{cji}}} \exp\left(-\frac{y_{cji}^2}{2\sigma_{cji}^2}\right).$$

The core center eccentricity of the i th fiber of the j th connector plug $\vec{r}_{pji}$ is expressed by a sum of the three vectors as

$$\vec{r}_{pji} = \vec{r}_{hji} + \vec{r}_{fji} + \vec{r}_{cji}. \quad (6)$$

In the connector loss simulation by the Monte Carlo method, the numerical value of each eccentricity vector was generated with a random function according to the probability density, and the each vector value was summed by (7).

$$x_{pji} = x_{hji} + x_{fji} + x_{cji}, \quad y_{pji} = y_{hji} + y_{fji} + y_{cji}. \quad (7)$$

2.2 Effect of mating force

Figure 3 shows force supporting points and deformations for two plugs mating. The plugs mating faces are angle polished in eight degrees. When mating force is applied between endfaces, the force generates forces of perpendicular to the endface and parallel to the endface. The perpendicular force is supported by the protruded optical fiber ends. The force parallel to the endface is supported by the contact points of the guide pins and the guide

holes, and elasticity deforms the guide hole and the pin minutely. As a result, the guide pin edges deflect. There is neither a movement in y-direction nor friction at the contact points but small deformations. Applied mating force Mf is supported by the edges of guide holes and guide pins. We assume that mating force Mf is evenly supported by two guide pins. The force component parallel to the endfaces $mf\delta$ is expressed as $mf\delta = (Mf/2) \cdot \sin(8)$. In the IEC standard, the center value of mating force is defined as 9.8 [N]. The center value of $mf\delta$ is derived as $mf\delta = 9.8/2 \cdot \sin(8) = 0.68$ [N]. In Appendix 1, Figure A-1 shows the measurement method of the deflections caused by this force. Figure A-2 shows the measurement results for two different materials.

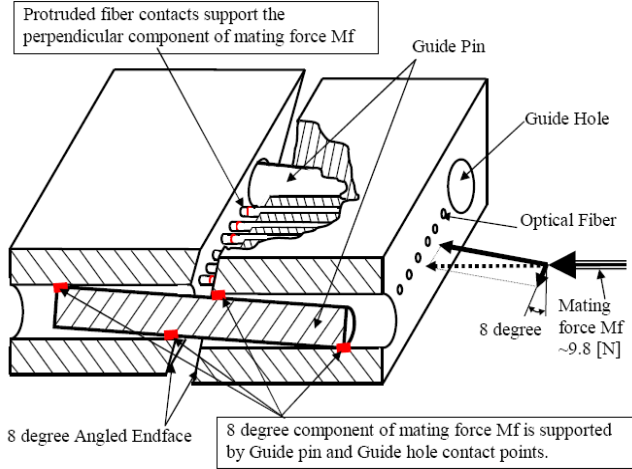


Figure 3. Mating force supporting points and deformations.

2.3 Guiding mechanism of mated plugs

For the calculation of alignment offset errors occurred in the guiding of APC MPO connectors, there are key parameters of diameters and pitches. To discuss the mated plugs guiding structure, we simply note plug numbers as #1 and #2 for $j=1$ and $j=2$. These parameters are listed in Table 1 for the case of plug #1 and plug #2 are mated as shown in Figure 4. In Table 1, distances between hole centers and pin centers R_1 , R_2 , L_1 , and L_2 are also listed. With these parameters, two coupling conditions are expressed as followings.

(1) Loose coupling, $|E_2 - E_1| < R_1 + R_2 + L_1 + L_2$. (8)

(2) Tight coupling, $|E_2 - E_1| \geq R_1 + R_2 + L_1 + L_2$. (9)

Loose coupling is the case that there is no width deformation and the axial direction friction is very small when guide pins are inserted into guide holes for mating. Tight coupling is the case that the guide hole pitches of two plugs have a large difference compared to the clearance between guide pin and guide hole. In this case when two plugs are mated, guide pins and guide holes will cause deformations in width direction (x-direction) and cause frictions when the guide pins are inserted into the guide holes. In this case, y-direction shift is limited.

Table 1. Definitions of guiding parameters

Item	Description
E_1	Plug#1 guide hole pitch
E_2	Plug#2 guide hole pitch
E_0	Guide pin pitch
H_{1R}	Plug#1 right guide hole diameter
H_{1L}	Plug#1 left guide hole diameter
H_{2R}	Plug#2 right guide hole diameter
H_{2L}	Plug#2 left guide hole diameter
I_R	Right guide pin diameter
I_L	Left guide pin diameter
$R_1 = (H_{1R} - I_R)/2$	Distance between plug #1 right hole and right pin
$L_1 = (H_{1L} - I_L)/2$	Distance between plug #1 left hole and left pin
$R_2 = (H_{2R} - I_R)/2$	Distance between plug #2 right hole and right
$L_2 = (H_{2L} - I_L)/2$	Distance between plug #2 left hole and left pin

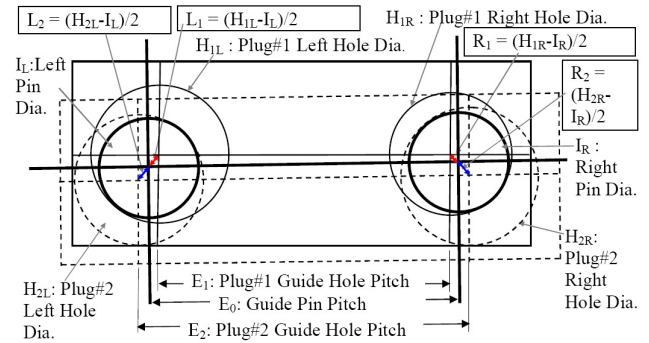


Figure 4. Plug#1 & Plug#2 alignment for loose coupling

2.4 Loose coupling condition.

For the loose coupling condition, the total offset is calculated as the sum of an offset caused by guide structure alignment error and a deformation "C_D" caused by guide pin and guide hole deformation due to applied mating force. Figure 4 shows loose coupling condition with $|E_2 - E_1| < R_1 + R_2 + L_1 + L_2$.

Due to the Y-direction shifting force component of mating force, guide hole centers and guide pin centers align in line for each side. In Figure 5(a) the center positions of the holes and pins are illustrated. "A" is plug #1 right hole center, "B" is plug #1 left hole center, "C" is plug #2 left hole center, and "D" is plug #2 right hole center. In this alignment, we assume the y-direction shifting force is uniformly supported by two guide pins and the angles φ_R and φ_L are also assumed to be the same values as $\varphi_R = \varphi_L = \varphi$, $\Delta E_R = (R_1 + R_2) \cos \varphi_R = (R_1 + R_2) \cos \varphi$, $\Delta E_L = (L_1 + L_2) \cos \varphi_L = (L_1 + L_2) \cos \varphi$,

with an assumption, $\Delta E_R + \Delta E_L = E_{20} - E_{10} \approx E_2 - E_1$ ^{*1}.

Where, $E_2 - E_1 = \{(R_1 + R_2) + (L_1 + L_2)\} \cos \varphi$,

$$\therefore \varphi = \cos^{-1} \left(\frac{E_2 - E_1}{R_1 + R_2 + L_1 + L_2} \right). \quad (10)$$

^{*1} In this report, H , P , and E have value ranges specified in Table 2.

$[E_{20} - E_2] \leq [(E_2^2 - (R_2 - L_2)^2 \sin^2 \varphi)^{0.5} - E_2] \leq 0.000017$ [μm]

This value is negligibly small. Therefore we can assume $E_{20} - E_{10} \approx E_2 - E_1$.

2.3.1 Plug #1 core position by guide pin alignment

The distance between two pin centers E_0 is expressed as;

$$E_0 = \frac{1}{2}(\sqrt{E_1^2 - (R_1 - L_1)^2 \sin^2 \varphi} + (L_1 + R_1) \cos \varphi + \sqrt{E_2^2 - (R_2 - L_2)^2 \sin^2 \varphi} + (L_2 + R_2) \cos \varphi). \quad (11)$$

By letting the center point of the line E_0 be the coordinate origin O, the i^{th} core position shift caused by the guiding structure of the Plug#1 is expressed as (x_{gli}, y_{gli}) .

$$x_{gli} = 250(i - 6.5) \left(\frac{\sqrt{E_1^2 - (R_1 - L_1)^2 \sin^2 \varphi}}{E_1} - 1 \right) + \frac{(L_1 - R_1)}{2} \cos \varphi, \quad (12)$$

$$y_{gli} = \left[\frac{\frac{(R_1 - L_1)}{E_0} (x_{gli} + R_1 \cos \varphi) + \frac{L_1 - R_1}{2}}{1 - \frac{(R_1 + L_1)}{E_0} \cos \varphi} + R_1 \right] \sin \varphi.$$

2.3.2 Plug #2 core position by guide pin alignment

In the same way as for Plug#2, the i^{th} core position shift of the Plug#2 is expressed as (x_{g2i}, y_{g2i}) .

$$x_{g2i} = 250(i - 6.5) \left(\frac{\sqrt{E_2^2 - (R_2 - L_2)^2 \sin^2 \varphi}}{E_2} - 1 \right) + \frac{(L_2 - R_2)}{2} \cos \varphi, \quad (13)$$

$$y_{g2i} = \left[\frac{\frac{(R_2 - L_2)}{E_0} (x_{g2i} + R_2 \cos \varphi) + \frac{L_2 - R_2}{2}}{1 - \frac{(R_2 + L_2)}{E_0} \cos \varphi} + R_2 \right] \sin \varphi.$$

We can calculate a nominal y value, y_{nominal} , with assumptions of $\cos \varphi \approx 0$, $(R_1 - L_1)/E_0 \approx 0$, $(R_2 - L_2)/E_0 \approx 0$, and by substituting R_1 , R_2 , L_1 , and L_2 into (12) and (13), we can derive (14) and (15):

$$y_{gli} = (1/2)(L_1 - R_1) \sin \varphi = (1/4) \{ (H_{1R} + H_{1L}) - (I_R + I_L) \} \sin \varphi, \quad (14)$$

$$y_{g2i} = (1/2)(L_2 - R_2) \sin \varphi = (1/4) \{ (H_{2R} + H_{2L}) - (I_R + I_L) \} \sin \varphi. \quad (15)$$

By letting the diameter of the guide pin holes and guide pins nominal value to be $H_{1L} = H_{1R} = ID_1$, $H_{2L} = H_{2R} = ID_2$, and $I_L = I_R = OD$, and by substituting $\sin \varphi = \alpha$ into (14) and (15), the nominal value of y without guide pin deformation is expressed as,

$$y_{\text{nominal}} = (1/2)(ID - OD)\alpha, \text{ where } 0 \leq \alpha \leq 1.$$

Here, by including the guide pin and guide hole deformation C_D as shown in Figure 5-(b), y_{nominal} is expressed as,

$$y_{\text{nominal}} = (1/2)(ID - OD)\alpha + C_D, \text{ where } 0 \leq \alpha \leq 1. \quad (16)$$

The C_D values depend on the material mechanical properties. In Figure 5-(b), two different material plugs with C_{D1} and C_{D2} are coupled. The “ y_{nominal} ” is the sum of two terms. One is an eccentricity caused by a guide pin clearance $(ID - OD)$ and a guide pin hole pitch difference α , and the other is a guide pin and guide pin hole deformation caused by the y-directional component of mating force. To cancel out this y-directional shift, we add “ Y_{offset} ” in the reverse direction with the same amount as “ y_{nominal} ”. The optimum value of Y_{offset} depends on each ferrule production conditions including molding condition, material, guide hole diameter, and guide hole pitch. By implementing a Y_{offset} in MT ferrule, the nominal value of y-direction offset

y_{nominal} can be minimized. Adding the Y_{offset} term to (12) and (13), the y-direction fiber hole position value of y_{gli} and y_{g2i} for mated plug are obtained as (17) and (18). This eccentricity y_{nominal} can be canceled out by adding the same size offset as y_{nominal} in the opposite direction to each MT Plug. This Y_{offset} cancels out the Y_{shift} for loose coupling case.

$$y_{gli} = \left[\frac{\frac{(R_1 - L_1)}{E_0} (x_{gli} + R_1 \cos \varphi) + \frac{L_1 - R_1}{2}}{1 - \frac{(R_1 + L_1)}{E_0} \cos \varphi} + R_1 \right] \sin \varphi - Y_{\text{offset}},$$

$$\text{where } Y_{\text{offset}} = \left(\frac{ID_1 - OD}{2} \alpha + C_{D1} \right). \quad (17)$$

$$y_{g2i} = \left[\frac{\frac{(R_2 - L_2)}{E_0} (x_{g2i} + R_2 \cos \varphi) + \frac{L_2 - R_2}{2}}{1 - \frac{(R_2 + L_2)}{E_0} \cos \varphi} + R_2 \right] \sin \varphi - Y_{\text{offset}},$$

$$\text{where } Y_{\text{offset}} = \left(\frac{ID_2 - OD}{2} \alpha + C_{D2} \right). \quad (18)$$

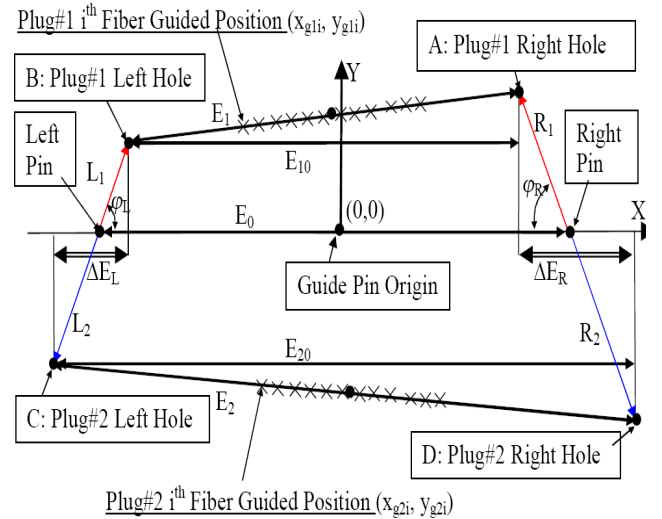


Figure 5-(a). Guide hole and guide pin position without deformation C_D

2.5 Tight coupling with a big difference of guide hole pitch

For the tight coupling case, φ will be 0 or π [rad] in Figure 5-(a). Figure 6 shows a tight coupling condition (9). In this condition, guide hole pitch is tight, and holes to pin clearances disappear and clearance based y-direction shift is eliminate. In this case, the Y_{offset} causes over compensation. The contact points have compression stress and deformation in the x-direction. The combination of the 8 degree component of mating force M_f in y-direction and the x-direction stress determine the alignment of guide holes and pins.

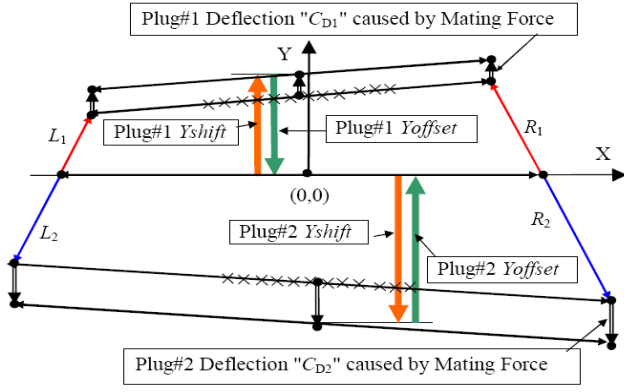


Figure 5(b). Guide hole and guide pin position with deformation C_D . Y-shift of each plug is the sum of the clearance related shift and the deformation C_D .

By substituting $\alpha = \sin \varphi = 0$ into (12) and (13) for x_{g1i} and x_{g2i} , into (17) and (18) for y_{g1i} and y_{g2i} , each core location offset caused by the guiding mechanism is expressed as (19) for plug #1 and plug #2. In this case, $Yoffset$ of each plug causes over compensation. Then fiber to fiber offsets become large.

$$\begin{aligned} x_{g1i} &= (1/2)(L_1 - R_1), & y_{g1i} &= -Yoffset_1, \\ x_{g2i} &= (1/2)(L_2 - R_2), & y_{g2i} &= -Yoffset_2. \end{aligned} \quad (19)$$

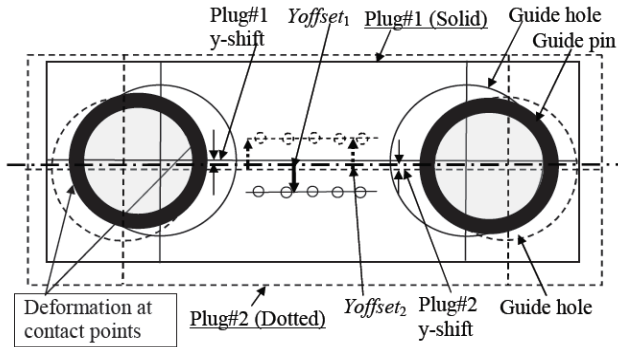


Figure 6. Tight coupling case with deformations

2.6 Total offset and angle error between mated fibers.

Eccentricity of each fiber of the connector plug is obtained as a sum of the following three factors.

- Eccentricity of the raw ferrule fiber hole.
- Eccentricity caused by the plug guiding structure.
- Deformation C_D caused by mating force.

The total eccentricities in Plug#1 of (x_{t1i}, y_{t1i}) and in Plug#2 of (x_{t2i}, y_{t2i}) are expressed as (20).

$$\begin{aligned} x_{t1i} &= x_{g1i} + x_{p1i}, & y_{t1i} &= y_{g1i} + y_{p1i} \\ x_{t2i} &= x_{g2i} + x_{p2i}, & y_{t2i} &= y_{g2i} + y_{p2i}. \end{aligned} \quad (20)$$

Lateral offset between each mated fiber pair is obtained by combining each fiber eccentricity of each plug. The lateral offset between i th mated fiber pair is obtained by (21).

$$d_i = \sqrt{(x_{t1i} - x_{t2i})^2 + (y_{t1i} - y_{t2i})^2}. \quad (21)$$

For APC-MPO connectors, two plugs are mated to match fiber channel numbers of multiple fibers. The lateral offset in the x-direction is expressed as a difference between the x-direction eccentricities of two plugs. The lateral offset in y-direction is expressed as a sum of y-direction eccentricities of mated plugs. An angle error between i th pair of fibers of mated plugs is obtained by expression (23) in Appendix-2. Connection loss of each i th fiber pair is obtained by substituting the values of d , θ , n_0 , λ , and ω into (1). An analytical prediction model for connector loss distribution based on connector plug dimension data has been established. The low-loss connection design attribute $Yoffset$ has been established for APC-MPO connectors by compensating for y-direction translation and thereby minimizing fiber to fiber offsets for plugs with different dimensions and different materials.

3. Alignment conditions for the different lot connector plugs.

3.1 Experimental conditions

In the previous section, $Yoffset$ was established as an MT-Ferrule attribute to reduce the fiber core offsets of an APC-MPO connector. Next, experimental methods and statistically modeling is employed to examine the low loss performance of plugs with different materials and guide pin hole size. Experimental and Monte Carlo simulation parameters are listed in Table 2. Figure 7 illustrates the two different plug designs. Two types of plugs of Type A and Type B made from different materials were prepared as listed in Table 3. For each type of plug, five 3 [m] 12 fiber cable assemblies with ends terminated with APC-MPO female plugs were prepared. The center values of the guide pin hole diameter ID , the center values of the guide pin diameters OD , and $(ID-OD)/2$ are shown in Table 3 for two different types of plugs. Since the guide pin hole pitches of both plug types were very close within 4600 ± 0.5 [μ m], by substituting $|E_2 - E_1| \approx 0$ into (10), we can approximate as $\varphi \approx 0$, then $\alpha \approx 1$. The measured deformation C_D for these two plugs is shown in Figure A-2. For the nominal mating force, C_D of Type A plug and Type B plug were approximately 0.6 [μ m] and 0.3 [μ m] respectively. The nominal values of $Yoffset$ for one side of Type A and Type B plug when connecting are 1.15 [μ m] and 0.55 [μ m]. The average guide hole pitch of Type A plugs were 0.5 [μ m] larger than that of Type B plugs. Connecting losses were measured for three combinations of plugs:

- (1) Type A plug and Type A plug (A-A).
- (2) Type B plug and Type B plug (B-B).
- (3) Type A plug and Type B plug (A-B).

In this experiment, in order to remove the connector loss fluctuations caused by end-face imperfections such as Fresnel reflections, loss measurements were performed with index matching oil on the connector end-faces. Prior to this experiment, we measured connector losses of plugs combinations of Type B and Type B without index matching oil and got low loss of 0.06 [dB] in the average and 0.21 [dB] for the 97% loss. The optical source was an edge-emitting LED with its center wavelength of 1310 [nm], a 12-channel mechanical switch was used as a channel selector, and a five [mm] diameter Ge photo detector was used. The stability of the measurement system was ± 0.01 [dB] during measurement.

3.2 Monte Carlo Simulation

Connection loss distribution was calculated by the following procedures. First of all, the constant values (C_D , n_0 , λ and $Yoffset$) were selected, then the plug dimensions and specified parameters (E , I , H , G_x , G_y , and Mf) were selected. Then for the mated plugs, the coupling conditions of tight or loose are established. In each case, random functions are applied to calculate (x_{gij} , y_{gij}). Each fiber MFC (x_{pji} , y_{pji}) in each plug is calculated by (7). In addition, the angle of fiber axis and mode field diameter ω of each fiber is calculated. From these values, an offset d_i between mated fibers of i th channel is calculated by (21). An angle Error θ_i is calculated by (23). Finally, by substituting these loss cause values into (1), a connection loss is obtained.

Table 2. Experimental and Monte Carlo Simulation Parameters

	Sign	Item	Value range	Std.
Offset [μm]	D_{ji}	Fiber hole dia.	125.3 -- 125.9 ^{*1}	$\sigma_D=0.6/6$
	$\vec{r}_h(x_h, y_h)$	Fiber hole eccentricity	0 -- 0.75 ^{*1}	$\sigma_h=1.5/6$
	a_{ji}	Fiber cladding diameter	124.8 -- 125.2 ^{*3}	$\sigma_a=0.4/6$
	$\vec{r}_c(x_c, y_c)$	Fiber core concentricity	< 0.5 ^{*4}	$\sigma_c=0.5/6$
	E	Guide hole pitch	4598 -- 4602 ^{*2}	$\sigma_E=2/6$
	H	Guide hole dia.	699.0 -- 699.6 ^{*2}	$\sigma_H=0.6/6$
	I	Guide pin dia.	698.4 -- 698.6 ^{*2}	$\sigma_I=0.2/6$
	$\vec{r}_f(x_f, y_f)$	Fiber eccentricity in fiber hole	$-(D-a)/2$ -- $+(D-a)/2$ ^{*5}	$\sigma_f=(D-a)/6$
Angle [deg.]	2ω	Mode field dia. at $\lambda=1310\text{nm}$	8.8 -- 9.6 ^{*4}	$\sigma_\omega=0.8/6$
	C	Fiber hole angle in x- and y-direction	< 0.2 ^{*2}	$\sigma_c=0.2/6$
	G_x, G_y	Endface angle in x- and y-direction	< 0.2 ^{*2}	$\sigma_g=0.2/6$
Other	Mf [N]	Mating force	7.8 -- 11.8 ^{*2}	$\sigma_{Mf}=4/6$
	n	Core index at $\lambda=1310\text{nm}$	1.4681 ^{*4}	
	λ [nm]	Wavelength of light	1310	

*1: US Conec specification.

*2: Our proposal for IEC Standard of APC-MPO Grade B connector.

*3: Market available fiber diameter.

*4: IEC Standard 60793-2-50 type B.1.3 Optical Fiber Specification.

*5: Fiber centering effect by adhesive is described by two dimensional Gaussian distribution with a standard deviation of 1/6 of clearance between hole and fiber.

Table 3. Key dimensions of sample plugs [μm]

Item	Type A	Type B
Nominal guide hole diameter ID	699.6	699.0
Nominal guide pin diameter OD	698.5	
$(ID - OD)/2$	0.55	0.25
Nominal pin and hole deformation C_D	0.6	0.3
Nominal value of $Yoffset$	1.15	0.55
Guide hole pitch E	4600.3	4599.7

3.3 Experimental and simulation results

Connector loss performances were measured for two different kinds of plugs as described in 3.1. The performances were also simulated by Monte Carlo method in Figure 9 and Figure 10. The 97% connection values of each experiment are listed in Table 4. The experimental and simulation results were closely matched. Figure 9-1 shows matings of plug combination of A-A. The experimental average values and the standard deviation

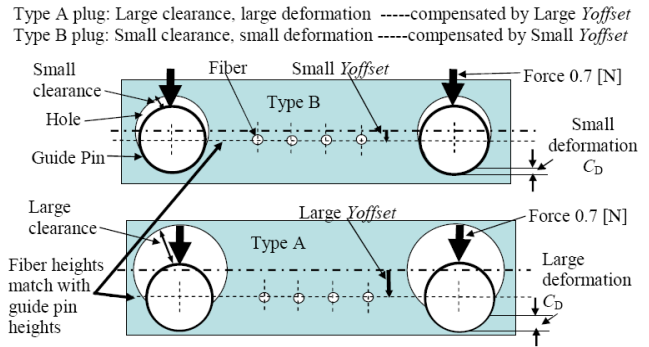


Figure 7. Y-direction alignment for two different material plugs. Plug A and Plug B are aligned with the common guide pins. Both of the fiber arrays are aligned at the same height even with the different size Yoffsets.

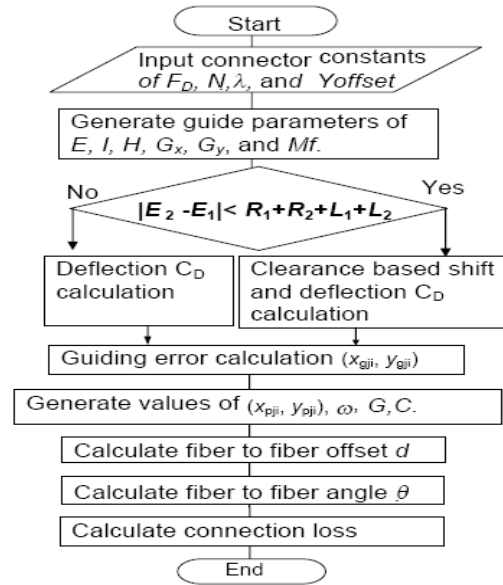


Figure 8. Flow chart of Monte Carlo simulation for MPO Connector loss estimation

values matched with simulation results. This figure shows that the connection losses of Type A plugs have a small loss dependence on fiber positions. Figure 9-2 shows connector loss dependence on fiber positions for B-B. The average and the standard deviation curves matched with the simulation results. Figure 9-3 shows connector losses between different kind plugs combination of A-B with different dimensions and different materials. The measured losses were very low of 0.08 [dB] as the average and 0.22 [dB] as the 97% value. This average loss is corresponding to the very small offset values around 0.65 [μm]. The proposed alignment error compensation design was verified. Fig. 10 shows cumulative loss distributions of the three plug combinations. Monte Carlo simulations for the same plug conditions of A-A and B-B closely matched and also with the experimental results well. The proposed connector loss calculation model was verified as accurate. The different plugs combination A-B show a slightly higher losses due to a guide pin pitch difference of 0.6 [μm].

4. Conclusions

An APC-MPO connector design method with Yoffset for low-loss connections is proposed. The design method was verified by experimental results for plugs combinations of different materials and different dimensional characteristics. A proposed geometrical alignment model for APC-MPO connectors was established and verified by comparing Monte Carlo simulations with empirical insertion loss results. Network owners utilizing standardized APC-MPO connectors based on these design parameters can obtain low insertion loss with cable assemblies supplied from multiple component vendors. This multi-fiber connector enables rapid deployment of dense single mode fiber networks for FTTH and WDM applications.

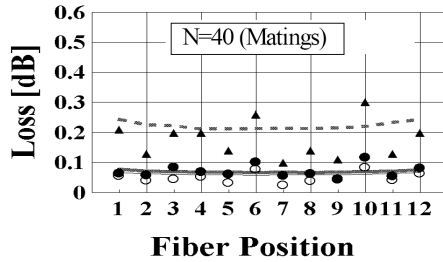


Figure 9-1. Connection loss dependence on fiber position for plugs combination of A-A. Plots are experimental results and lines are simulation results. Dotted line and triangles are the 97% value. Thick solid line and filled circles are the average. Thin solid line and empty circles are the standard deviation. The average loss is 0.07 [dB] and the 97% is 0.20 [dB].

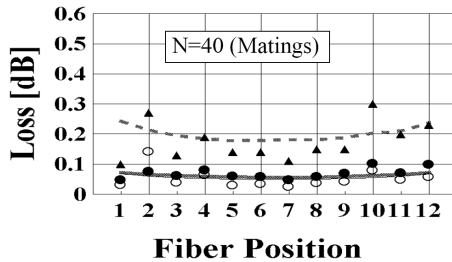


Figure 9-2. Connection loss dependence on fiber position for plugs combination of B-B. The average loss is 0.07 [dB] and the 97% is 0.19 [dB].

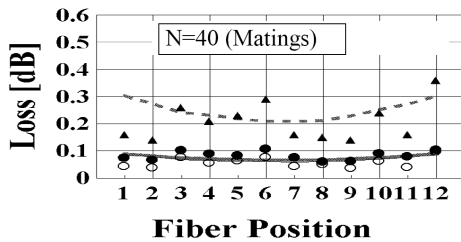


Figure 9-3. Connection loss dependence on fiber position for plugs combination of A-B. The average loss is 0.08 [dB] and the 97% is 0.22 [dB].

Table 4. 97% loss value of different plug combinations

Plug combination	Test results [dB]	Simulation [dB]
A-A	0.20	0.21
B-B	0.19	0.20
A-B	0.22	0.23

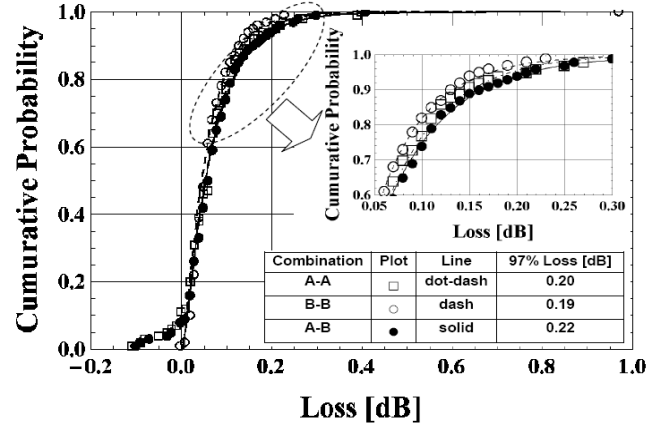


Figure 10. Connection loss distribution for Type A plugs and Type B plugs. Plots are experimental results and lines are simulation results.

Appendix-1

Guide pin and guide hole deformation dependence on applied force at the pin edge is measured by the set up shown in Figure A-1. A precision linear scale with a resolution of 1/100 [μm] is used. The guide pin and guide hole deformation dependence on applied force on to the pin inserted into two different material MTs are measured. The measurement results are shown in Figure A-2. The deformation of the guide pin increases proportional to the applied force. We define the deformation constant C_D as the deformation with 0.7 [N] force corresponding to the nominal mating force value of 9.8 [N]. The measured deformation of Type A material was $C_D = 0.6$ [μm], and for Type B material $C_D = 0.3$ [μm].

Appendix-2

The calculation method of the angle between the mated fibers is described in this appendix. Angle between two mated fibers is illustrated in Figure. A-3. As listed in Table 1, fiber hole axis has an angle C ($-0.2 \leq C \leq 0.2$) from Z-axis and an angle ϕ_e ($0 \leq \phi_e \leq 2\pi$) in rotational direction uniformly. The value of C is generated by Gaussian distribution of $m = 0$ and $\sigma = 0.2/3$. The value of ϕ_e is generated by a uniform random distribution. The plug end face has an angle G from Z-axis and an angle ϕ_p in rotational direction. The value of G is generated from the followings. $G = (G_x^2 + G_y^2)^{0.5}$, $\phi_p = \tan^{-1}(G_x/G_y)$, where $-0.2 \leq G_x \leq 0.2$, and $7.8 \leq G_y \leq 8.2$. The value of G_x and G_y is generated by Gaussian distribution of $m = 0$ with $\sigma = 0.2/3$. The value of G_y is generated by Gaussian distribution of $m = 8$ with $\sigma = 0.2/3$.

Now, a fiber axis direction of Plug #1 is expressed by solid geometry as "Directional cosine" of l_1 , m_1 , and n_1 with a formula of $l_1^2 + m_1^2 + n_1^2 = 1$. The "Directional cosine" of Plug#1 fiber angle C is expressed by a vector as $V_{1f} = (l_{1f}, m_{1f}, n_{1f})$,

where, $m_{1f} = r_{1f} \sin \phi_{1f} = \sin C_1 \sin \phi_{1f}$,

$l_{1f} = r_{1f} \cos \phi_{1f} = \sin C_1 \cos \phi_{1f}$, $n_{1f} = 1 \cos C_1 = \cos C_1$.

Plug endface angle G is expressed by a vector as

$V_{1p} = (l_{1p}, m_{1p}, n_{1p})$, where, $m_{1p} = r_{1p} \sin \phi_{1p} = \sin G_1 \sin \phi_{1p}$,

$l_{1p} = r_{1p} \cos \phi_{1p} = \sin G_1 \cos \phi_{1p}$, $n_{1p} = 1 \cos G_1 = \cos G_1$.

The fiber core axis of the plug #1 is obtained by the sum of two vectors as $V_1 = V_{1f} + V_{1p}$, $V_{1f} = V_{1p} = 1$.

V_1 is expressed by "Directional cosine" notation as,

$l_1 = (l_{1f} + l_{1p}) / L_1$, $m_1 = (m_{1f} + m_{1p}) / L_1$, $n_1 = (n_{1f} + n_{1p}) / L_1$,

Where, $L_1 = \{ (l_{1f} + l_{1p})^2 + (m_{1f} + m_{1p})^2 + (n_{1f} + n_{1p})^2 \}^{0.5}$.

The fiber core axis angle of Plug #2 is expressed in the same way.

$V_2 = V_{2f} + V_{2p}$, $V_{2f} = V_{2p} = 1$, $l_2 = (l_{2f} + l_{2p}) / L_2$,

$m_2 = (m_{2f} + m_{2p}) / L_2$, $n_2 = (n_{2f} + n_{2p}) / L_2$,

where, $L_2 = \{ (l_{2f} + l_{2p})^2 + (m_{2f} + m_{2p})^2 + (n_{2f} + n_{2p})^2 \}^{0.5}$.

Then the angle between two fiber axes in mated plugs is expressed as, $\theta = \cos^{-1} (l_1 l_2 + m_1 m_2 + n_1 n_2)$. (23)

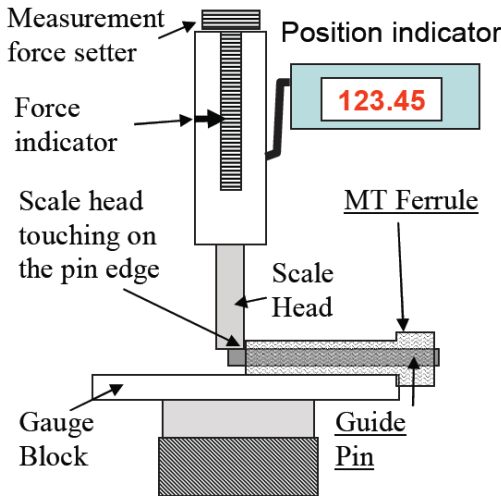


Figure A-1. Pin edge deformation measurement

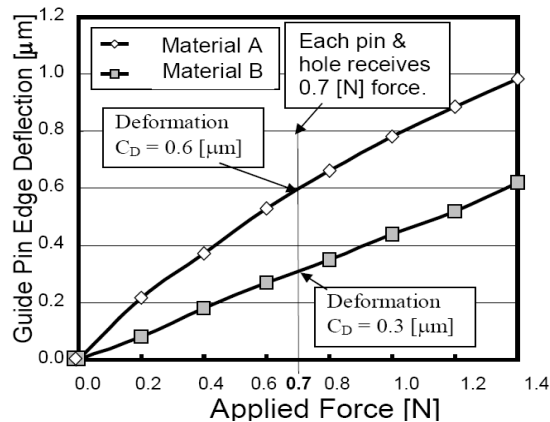


Figure A-2. Pin edge deformation measured results

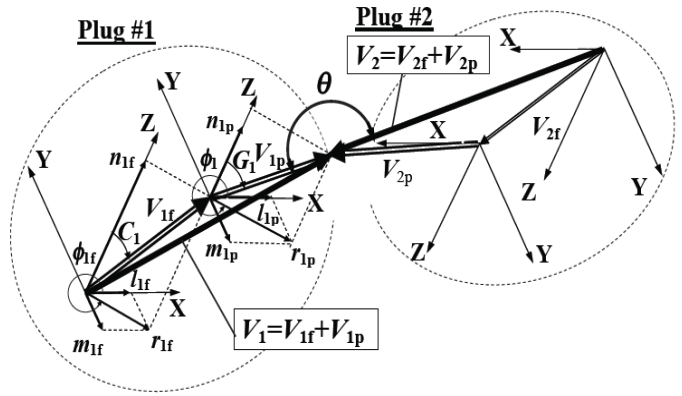


Figure A-3. Tilt angle θ between Plug#1 and Plug#2.

5. Acknowledgments

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