2.9. Fiber Connectorization

The installation of a fiber optic network may require hundreds to thousands of connections between two fibers to be made. The quality of the conncection is measured by the insertion and reflection losses introduced. Two major types of connections are made today - the splice, in which two bare pieces of fiber are held in close contact, and through the use of connectors, much like the BNC use for coax or RJ-45 for twisted-pair.

2.9.1. Fiber Splicing

A fiber splice is made in two ways - either a mechanical splice in which two fibers are placed abutting each other and held mechanically, or the fusion splice, in which two fibers are melted together using an electrical arc.

There are two types of loss experienced in fiber splicing (and connectorzation) - intrinsic and extrinsic. Intrinsic losses are related to the geometries of the fibers being spliced, while extrinsic losses are related to the relative alignment of the fibers after being spliced; therefore, the actual splicing procedure can have a large effect on extrinsic losses.

Intrinsic losses

Intrinsic losses are due to three mismatches between two fibers - core size mismatch, numerical aperture mismatch, and mode-field diameter mismatch, and fresnel reflections from the interfaces.

Loss due to core size mismatch is given by

$$Loss_{core} = -10\log\left(\frac{a_2}{a_1}\right)^2,$$

where a_1 and a_2 are the core sizes and $a_1 \geq a_2$. This loss measure is more applicable to multi-mode fiber.

Loss due to numerical aperture mismatch is given by

$$Loss_{NA} = -10\log\left(\frac{NA_2}{NA_1}\right)^2,$$

where $NA_1 \geq NA_2$. Again, this best applies to multi-mode fiber.

Coupling loss for single mode fiber is calculated based upon the mismatch in mode-field diameter

$$L_{\text{MFD}} = -10\log\left[\frac{4}{(MFD_1/MFD_2 + MFD_2/MFD_1)^2}\right]$$

This relation essentially takes both core and numerical mismatches into account and typically gives the most accurate estimate of intrinsic coupling loss.

Connecting, or splicing, two single-mode fibers together is a very common task. However, these fibers may have different MFDs. Since the MFD is specified for any fiber, it is easy to calculate the coupling loss due to mode mismatch via the expression

The other intrinsic loss mechanisms is due to Fresnel reflections at the interfaces of the fibers and air. This can be nearly eliminated by using index-matching fluid in the splice process to fill the small gap between fibers. Backreflections are also very small in fusion splices since the fibers are melted together.

Extrinsic losses

These losses result from fiber misalignments during the splice process - lateral misalignment, angular misalignment, and end separation or gap. In the following equations, it is assumed that the two fiber geometries are identical and that the fibers are single-mode. Expressions that are valid for multi-mode fibers can be found in the textbook; for multi-mode fibers, it is assumed that the core area is uniformly illuminiated due to the superposition of the many modes.

Loss due to lateral displacement is given by

$$Loss_{lat} = -10\log\left[\mathrm{e}^{(-d/w_0)^2}\right],$$

where d is the displacement between the center of the fiber cores and $w_0 = MFD/2$ is the mode field radius. It should also be recognized that lateral displacement may occur due to concentricity errors during fiber manufacture.

Loss due to angular displacement is given by

$$Loss_{ang} = -10\log\left[\mathrm{e}^{-T^2}\right],$$

where $T = n\pi w_0 \sin(\theta)/\lambda_f$, and θ is the tilt angle between the fiber axes.

Loss due to end separation is given by

$$Loss_{end} = -10\log\left[\frac{1}{S^2+1}\right],$$

where $S = z\lambda_f/(2\pi n w_0^2)$, and z is the end to end displacement.

2.9.2. Connectors

Connectorized fiber has much greater flexibility than fiber that's been mechanically or fusion spliced, but the performance is worse. The major performance characteristics of connectors are insertion loss, return loss, and repeatability.

Insertion loss is the amount of power lost in transmission due to the connection. Average insertion losses are 0.25 dB, with a maximum of about 0.5 dB. For comparison, insertion loss for fusion-spliced fiber is below 0.15 dB.

Return loss quantifies how much power is reflected backwards from the connection:

$$RL(dB) = 10\log(R),$$

where R is the intensity reflectance from the connection. Two methods are used to reduce return loss. The first is very careful polishing of the fiber endfaces. Many connectors make physical contact to minimize Fresnel reflections, and polishing is a critical issue to maintain uniform flat contact. Return loss is typically -55 dB. Using angled physical contact, in which the fiber endfaces are polished at an 8 degree angle can reduce the return loss to -75 dB. Light reflected off the angled face exceeds the numerical aperture of the fiber and exits through the cladding. These connectors are more complicatad as some form of keying mechanism must be used to ensure proper orientation.

Since connectors are used primarily for temporary connections, the issue of repeatability is an essential one. Insertion loss increases after a number of connections are made. Typical numbers are in increase of up to 0.2 dB per 500 connections.

There are many styles of connectors used today in the fiber industry. The most popular are ST, SC, and FC. Unfortunatly, however, there is no standard in the industry.