Fiber splices

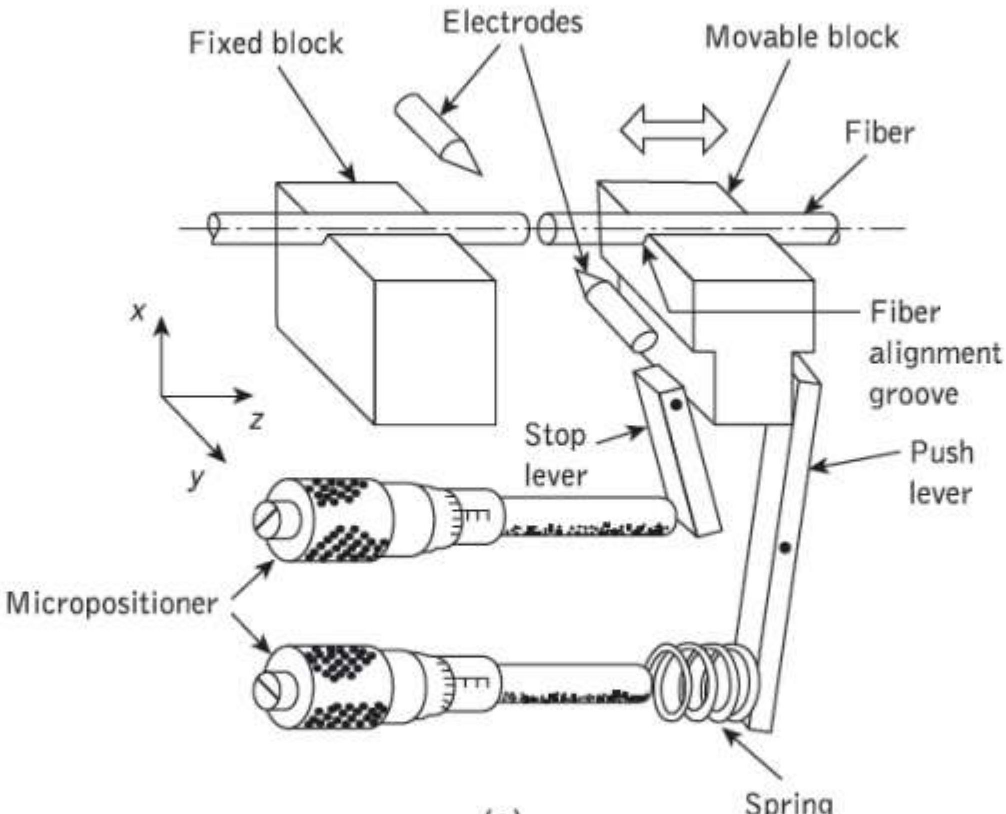
Fiber Splicing

A permanent joint formed between two individual optical fibers in the field or factory is known as a fiber splice. Fiber splicing is frequently used to establish long-haul optical fiber links where smaller fiber lengths need to be joined, and there is no requirement for repeated connection and disconnection.

Splices may be divided into two broad categories depending upon the splicing technique utilized. These are

- Fusion splicing or welding
- Mechanical splicing

Fusion splicing



(a)

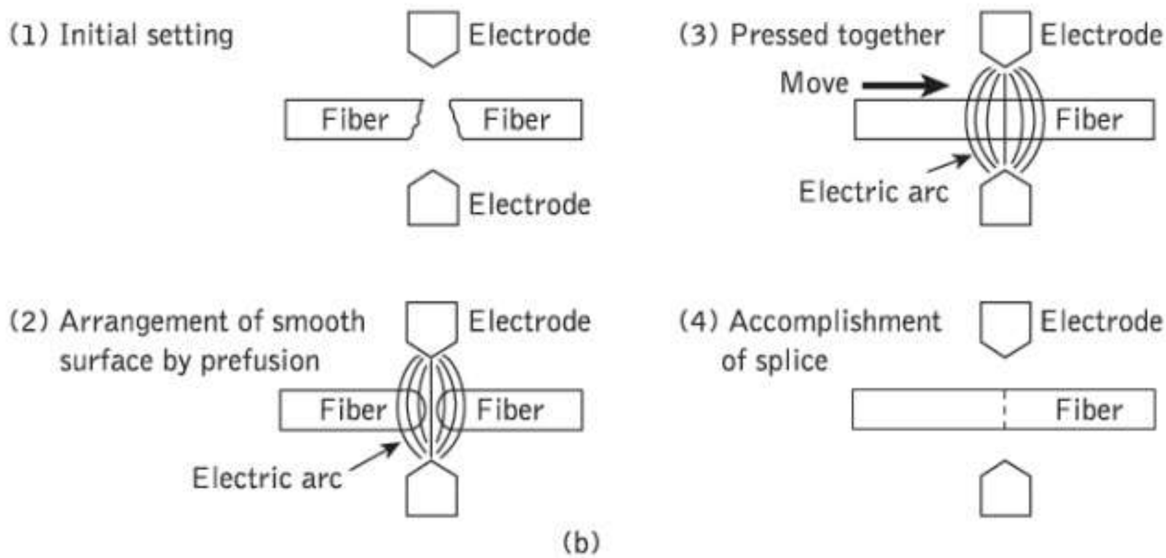


Figure 2.21 Electric arc fusion splicing: (a) an example of fusion splicing apparatus; (b) schematic illustration of the prefusion method for accurately splicing optical fibers

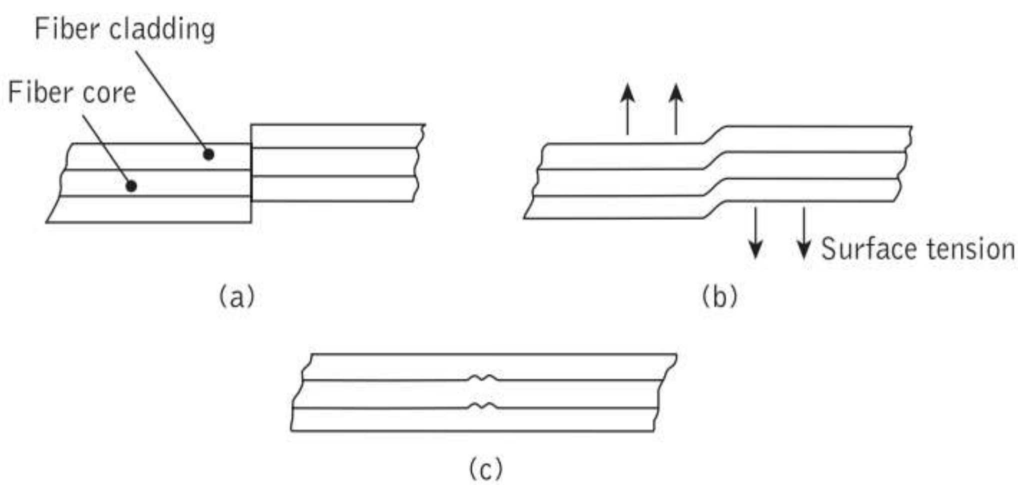


Figure :Self-alignment phenomenon which takes place during fusion splicing:

(a) before fusion; (b) during fusion; (c) after fusion

<u>Mechanical splices</u>:

Snug tube splice

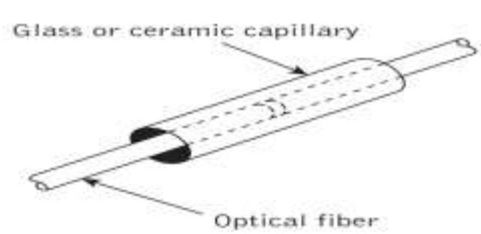


Figure :snug tube splice.

- This snug tube splice is illustrated in Figure and may utilize a glass or ceramic capillary with an inner diameter just large enough to accept the optical fibers.
- Transparent adhesive (e.g. epoxy resin) is injected through a transverse bore in the capillary to give mechanical sealing and index matching of the splice.
- Average insertion losses as low as 0.1 dB have been obtained with multimode graded index and single-mode fibers using ceramic capillaries.
- snug tube splices exhibit problems with capillary tolerance requirements. Hence as a commercial product they may exhibit losses of up to 0.5 dB

Loose tube splice

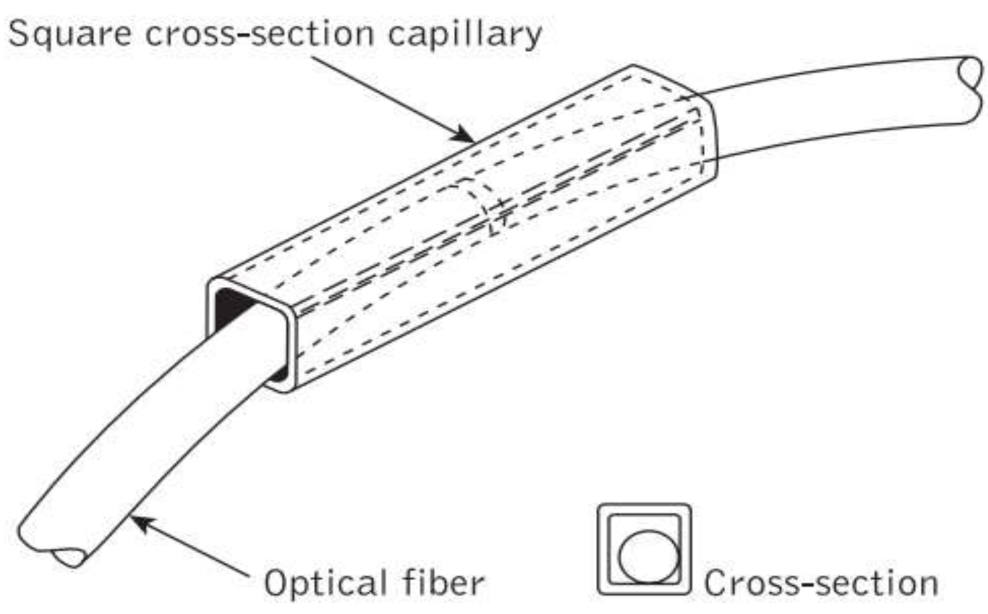


Figure: loose tube splice utilizing square cross-section capillary

- A mechanical splicing technique which avoids the critical tolerance requirements of the snug tube splice is shown in Figure .
- This loose tube splice uses an oversized square-section metal tube which easily accepts the prepared fiber ends.
- Transparent adhesive is first inserted into the tube followed by the fibers. The splice is self-aligning when the fibers are curved in the same plane, forcing the fiber ends simultaneously into the same corner of the tube, as indicated in Figure .
- Mean splice insertion losses of 0.073 dB have been achieved using multimode graded index fibers with the loose tube approach.

V-groove splices

- V-groove splices formed by sandwiching the butted fiber ends between a V-groove glass substrate and a flat glass retainer plate, as shown in Figure ,have also proved very successful in the laboratory.
- Splice insertion losses of less than 0.01 dB when coupling single-mode fibers have been reported using this technique.
- However, reservations are expressed regarding the field implementation of these splices with respect to manufactured fiber geometry, and housing of the splice in order to avoid additional losses due to local fiber bending.

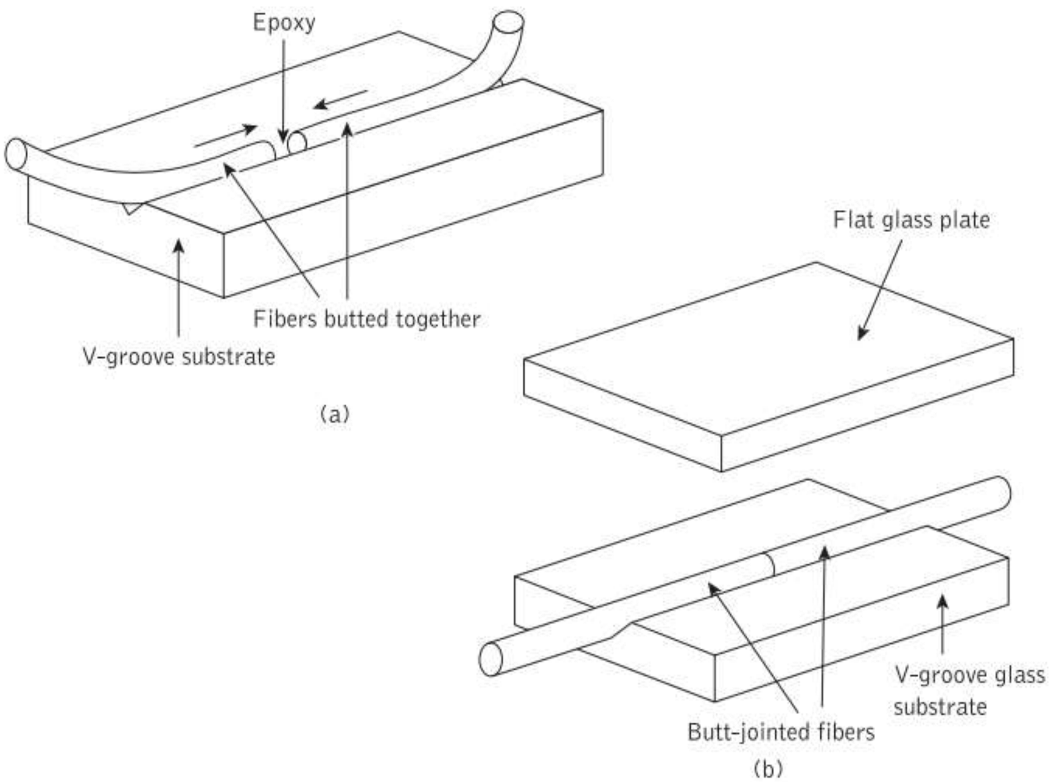


Figure : V-groove splices

Elastomeric splice

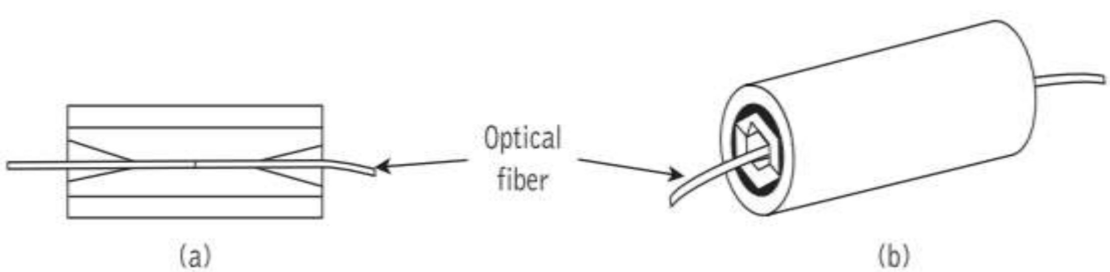


Figure : The elastomeric splice (a) cross-section; (b) assembly

- A further variant on the V-groove technique is the elastic tube or elastomeric splice shown in Figure . The device comprises two elastomeric internal parts, one of which contains a V-groove.
- An outer sleeve holds the two elastic parts in compression to ensure alignment of the fibers in the V-groove, and fibers with different diameters tend to be centered and hence may be successfully spliced. Although originally intended for multimode fiber connection, the device has become a widely used commercial product which is employed with single-mode fibres, albeit often as a temporary splice for laboratory investigations.
- The splice loss for the elastic tube device was originally reported as 0.12 dB or less but is generally specified as around 0.25 dB for the commercial product . In addition, index-matching gel is normally employed within the device to improve its performance.

Springroove® splice

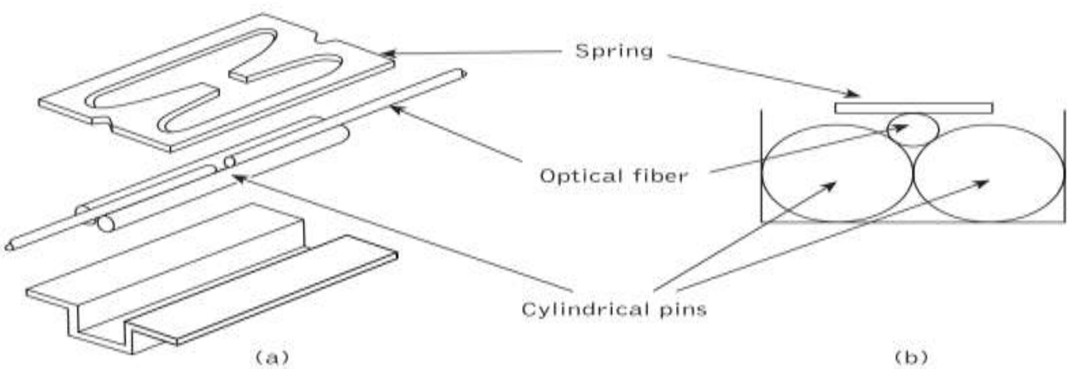


Figure: The Springroove® splice (a) expanded overview of the splice; (b) schematic cross-section of the splice

- A slightly more complex groove splice known as the Springroove® splice utilized a bracket containing two cylindrical pins which serve as an alignment guide for the two prepared fiber ends.
- The cylindrical pin diameter was chosen to allow the fibers to protrude above the cylinders, as shown in Figure. An elastic element (a spring) was used to press the fibers into a groove and maintain the fiber end alignment, as illustrated in Figure (b).
- The complete assembly was secured using a drop of epoxy resin. Mean splice insertion losses of 0.05 dB were obtained using multimode graded index fibers with the Springroove® splice. This device found practical use in Italy.

Fiber alignment and joint loss

Fiber alignment loss

INTRODUCTION:

- when the two jointed fiber ends are smooth and perpendicular to the fiber axes, and the two fiber axes are perfectly aligned, a small proportion of the light may be reflected back into the transmitting fiber causing attenuation at the joint. This phenomenon, known as **Fresnel reflection**, is associated with the step changes in refractive index at the jointed interface (i.e. glass–air–glass).
- The magnitude of this partial reflection of the light transmitted through the interface may be estimated using the classical Fresnel formula for light of normal incidence and is given by

$$r = \left(\frac{n_1 - n}{n_1 + n}\right)^2$$

where r is the fraction of the light reflected at a single interface, n1 is the refractive index of the fiber core and n is the refractive index of the medium between the two jointed fibers (i.e. for air n = 1).

The loss in decibels due to Fresnel reflection at a single interface is given by:

$$\text{Loss}_{\text{Fres}} = -10 \log_{10}(1 - r)$$

- The effect of Fresnel reflection at a fiber–fiber connection can be reduced to a very low level through the use of an index-matching fluid in the gap between the jointed fibers. When the index-matching fluid has the same refractive index as the fiber core, losses due to Fresnel reflection are in theory eradicated.
- Fresnel reflection is only one possible source of optical loss at a fiber joint. A potentially greater source of loss at a fiber–fiber connection is caused by misalignment of the two jointed fibers.
- Any deviations in the geometrical and optical parameters of the two optical fibers which are jointed will affect the optical attenuation (insertion loss) through the connection. It is not possible within any particular connection technique to allow for all these variations.

There are inherent connection problems when jointing fibers

(a) different core and/or cladding diameters;

(b) different numerical apertures and/or relative refractive index differences;

(c) different refractive index profiles;

(d) fiber faults (core ellipticity, core concentricity, etc.).

- The losses caused by the above factors together with those of Fresnel reflection are usually referred to as intrinsic joint losses.
- Examples of possible misalignment between coupled compatible optical fibers are illustrated in Figure

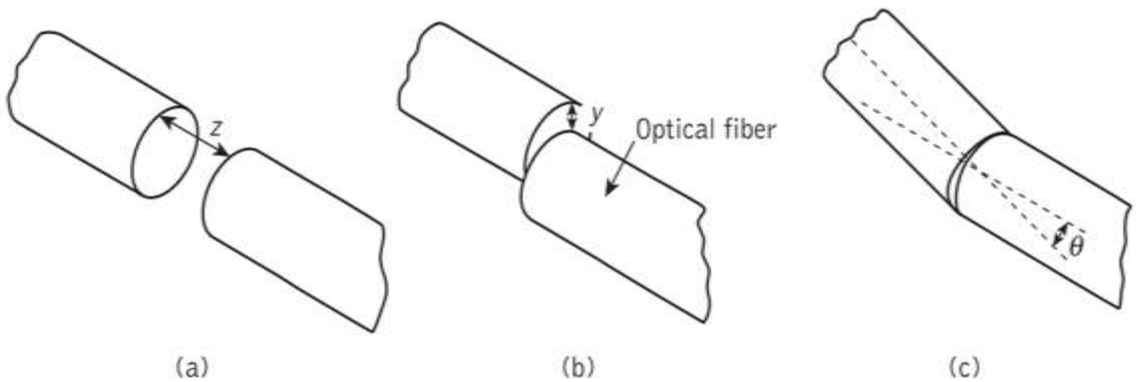


Figure: The three possible types of misalignment which may occur when jointing compatible optical fibers: (a) longitudinal misalignment; (b) lateral misalignment; (c) angular misalignment

Insertion loss due to lateral and longitudinal misalignment

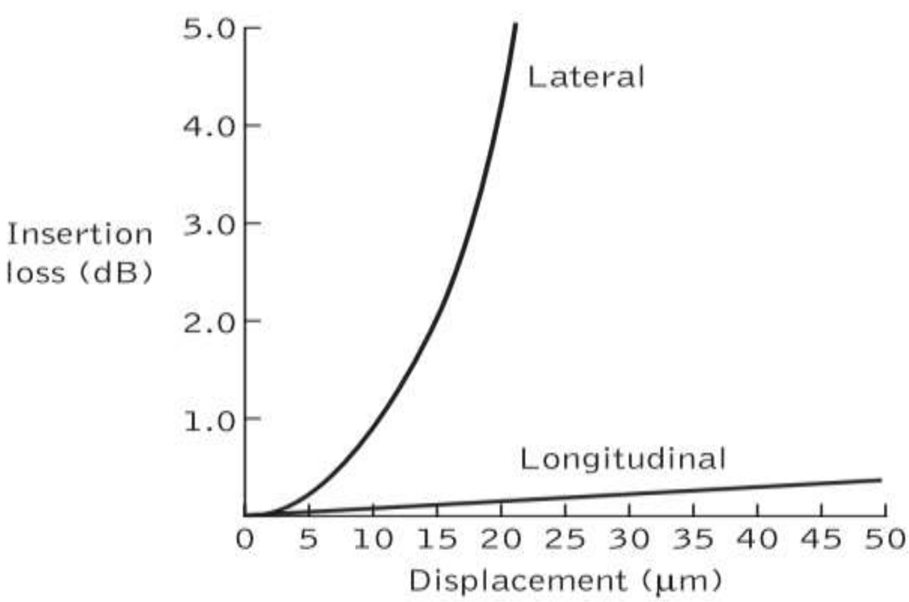


Figure : insertion loss due to lateral and longitudinal misalignment for a graded index fiber of 50 μm core diameter.

Insertion loss due to angular misalignment for joints

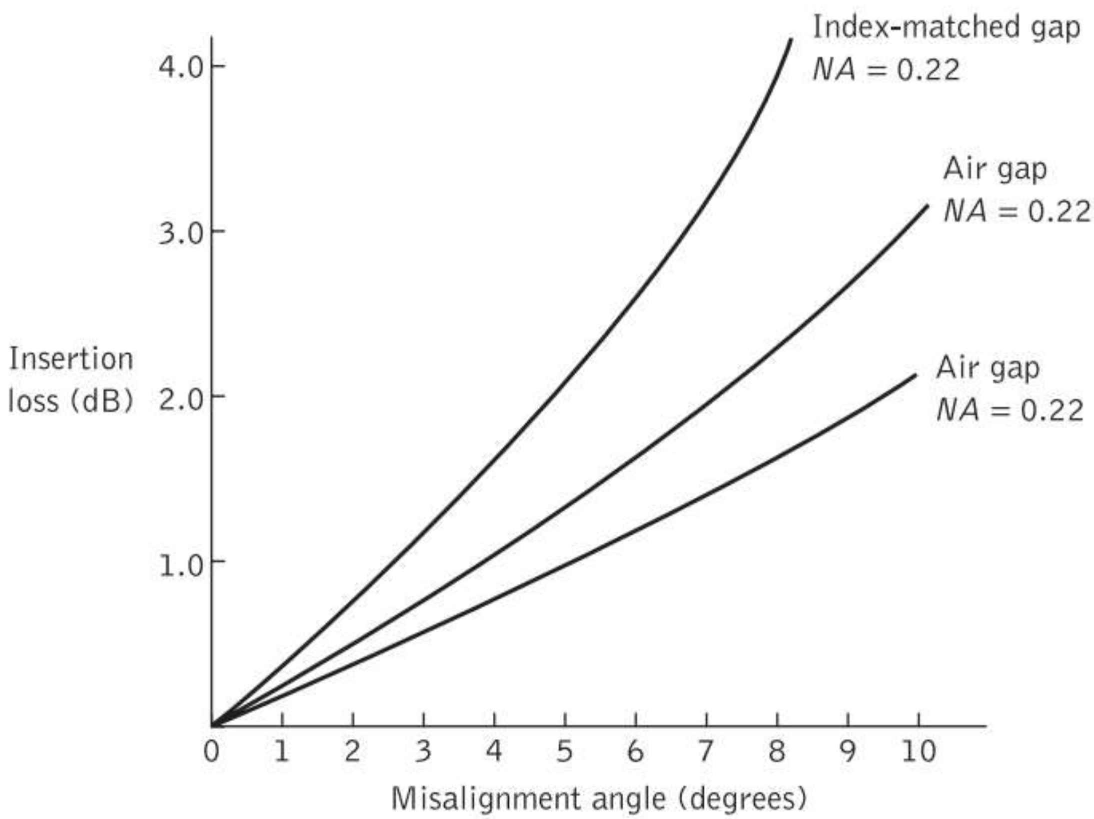


Figure: insertion loss due to angular misalignment for joints in two multimode step index fibers with numerical apertures of 0.22 and 0.3.

Fiber joint losses

Multimode fiber joints:

- Here some of the expressions used to calculate losses due to lateral and angular misalignment of optical fiber joints. Longitudinal misalignment is not discussed in detail as it tends to be the least important effect and may be largely avoided in fiber connection.
- Lateral misalignment reduces the overlap region between the two fiber cores. Assuming uniform excitation of all the optical modes in a multimode step index fiber, the overlapped area between both fiber cores approximately gives the lateral coupling efficiency η_{lat}. Hence, the lateral coupling efficiency for two similar step index fibers may be written as

$$\eta_{\mathrm{lat}} \simeq \frac{16(n_1/n)^2}{[1+(n_1/n)]^4}\frac{1}{\pi}\left\{2\cos^{-1}\left(\frac{y}{2a}\right)-\left(\frac{y}{a}\right)\left[1-\left(\frac{y}{2a}\right)^2\right]^{\frac{1}{2}}\right\}$$

where n1 is the core refractive index, n is the refractive index of the medium between the fibers, y is the lateral offset of the fiber core axes, and a is the fiber core radius.

The lateral misalignment loss in decibels may be determined using:

$$\text{Loss}_{\text{lat}} = -10 \log_{10} \eta_{\text{lat}} \text{ dB}$$

- Lateral misalignment loss in multimode graded index fibers assuming a uniform distribution of optical power throughout all guided modes was calculated by Gloge.
- He estimated that the lateral misalignment loss was dependent on the refractive index gradient α for small lateral offset and may be obtained from:

$$L_t = \frac{2}{\pi}\left(\frac{y}{a}\right)\left(\frac{\alpha+2}{\alpha+1}\right) \quad \text{for } 0 \le y \le 0.2a$$

where the lateral coupling efficiency was given by:

$$\eta_{\text{lat}} = 1 - L_t$$

With a parabolic refractive index profile where α = 2

$$L_t = \frac{8}{3\pi}\left(\frac{y}{a}\right) = 0.85\left(\frac{y}{a}\right)$$

This analysis was also extended to step index fibers (where α = ∞) and gave lateral misalignment losses of 0.64(y/a) and 0.5(y/a) for the cases of guided modes only and both guided plus leaky modes respectively.

- Angular misalignment losses at joints in multimode step index fibers may be predicted with reasonable accuracy using an expression for the angular coupling efficiency η_{ang} given by

$$\eta_{\text{ang}} \simeq \frac{16(n_1/n)^2}{[1 + (n_1/n)]^4}\left[1 - \frac{n\theta}{\pi n_1(2\Delta)^{\frac{1}{2}}}\right]$$

where θ is the angular displacement in radians and Δ is the relative refractive index difference for the fiber.

- The insertion loss due to angular misalignment may be obtained from the angular coupling efficiency in the same manner as the lateral misalignment loss following:

$$\text{Loss}_{\text{ang}} = -10 \log_{10} \eta_{\text{ang}}$$

The formulas given in Eqs predict that the smaller the values of Δ, the larger the insertion loss due to angular misalignment. This appears intuitively correct as small values of Δ imply small numerical aperture fibers, which will be more affected by angular misalignment

Two multimode step index fibers have numerical apertures of 0.2 and 0.4, respectively, and both have the same core refractive index of 1.48. Estimate the insertion loss at a joint in each fiber caused by a 5° angular misalignment of the fiber core axes. It may be assumed that the medium between the fibers is air.

Solution: The angular coupling efficiency is given by Eq. (5.8) as:

$$\eta_{\text{ang}} \simeq \frac{16(n_1/n)^2}{[1 + (n_1/n)]^4}\left[1 - \frac{n\theta}{\pi n_1(2\Delta)^{\frac{1}{2}}}\right]$$

The numerical aperture is related to the relative refractive index difference following Eq. (2.10) where:

$$NA \simeq n_1(2\Delta)^{\frac{1}{2}}$$

Hence:

$$\eta_{\text{ang}} \simeq \frac{16(n_1/n)^2}{[1 + (n_1/n)]^4}\left[1 - \frac{n\theta}{\pi NA}\right]$$

For the $NA = 0.2$ fiber:

$$\eta_{\text{ang}} \simeq \frac{16(1.48)^2}{[1 + 1.48]^4}\left[1 - \frac{5\pi/180}{\pi 0.2}\right]$$
$$= 0.797$$

The insertion loss due to the angular misalignment may be obtained from Eq. (5.9), where:

$$\text{Loss}_{\text{ang}} = -10 \log_{10} \eta_{\text{ang}} = -10 \log_{10} 0.797$$
$$= 0.98 \text{ dB}$$

For the $NA = 0.4$ fiber:

$$\eta_{\text{ang}} \simeq 0.926\left[1 - \frac{5\pi/180}{\pi 0.4}\right]$$

$\simeq$

0.862

The insertion loss due to the angular misalignment is therefore:

$$Loss_{\text{ang}} = -10 \log_{10} 0.862$$

- Hence it may be noted from Example that the insertion loss due to angular misalignment is reduced by using fibers with large numerical apertures.
- This is the opposite trend to the increasing insertion loss with numerical aperture for fiber longitudinal misalignment at a joint.

❑ Factors causing fiber–fiber intrinsic losses were listed

- The major ones comprising a mismatch in the fiber core diameters,
- A mismatch in the fiber numerical apertures and differing fiber refractive index profiles.

Connections between multimode fibers with certain of these parameters being different can be quite common, particularly when a pigtailed optical source is used, the fiber pigtail of which has different characteristics from the main transmission fiber. Moreover, as indicated previously, diameter variations can occur with the same fiber type.

Assuming all the modes are equally excited in a multimode step or graded index fiber, and that the numerical apertures and index profiles are the same, then the loss resulting from a mismatch of core diameters.

$$\text{Loss}_{\text{CD}} = \begin{cases} -10 \log_{10}\left(\dfrac{a_2}{a_1}\right)^2 \text{ (dB)} & a_2 < a_1 \\ 0 \quad \text{(dB)} & a_2 \geq a_1 \end{cases}$$

where a1 and a2 are the core radii of the transmitting and receiving fibers respectively.

It may be observed from Eq. that no loss is incurred if the receiving fiber has a larger core diameter than the transmitting one. In addition, only a relatively small loss (0.09 dB) is obtained when the receiving fiber core diameter is 1% smaller than that of the transmitting fiber.

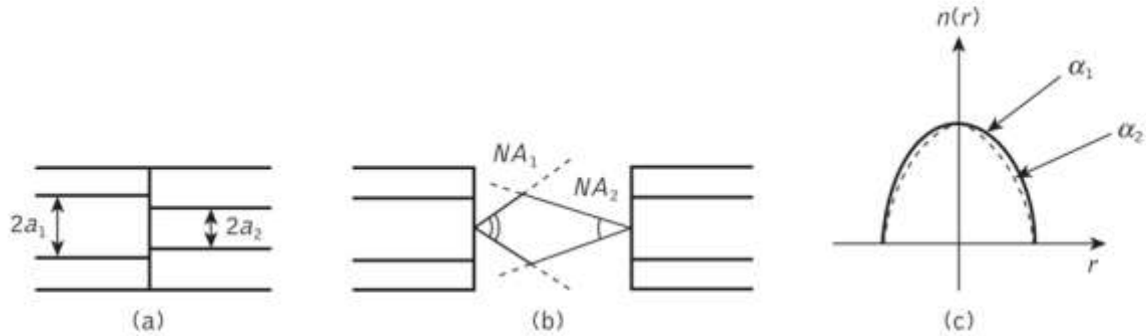


Figure: Some intrinsic coupling losses at fiber joints: (a) core diameter mismatch; (b) numerical aperture mismatch; (c) refractive index profile difference

- When the transmitting fiber has a higher numerical aperture than the receiving fiber, then some of the emitted light rays will fall outside the acceptance angle of the receiving fiber and they will therefore not be coupled through the joint.

Assuming a uniform modal power distribution, and fibers with equivalent refractive index profiles and core diameters, then the loss caused by a mismatch of numerical apertures can be obtained from

$$\mathrm{Loss_{NA}} = \begin{cases} -10\log_{10}\left(\dfrac{NA_2}{NA_1}\right)^2 \ (\mathrm{dB}) & NA_2 < NA_1 \\ 0 \qquad\qquad\qquad\quad\ \ (\mathrm{dB}) & NA_2 \geq NA_1 \end{cases}$$

where NA1 and NA2 are the numerical apertures for the transmitting and receiving fibers respectively. Equation is valid for both step and graded index* fibers and in common with Eq. it demonstrates that no losses occur when the receiving parameter (i.e. numerical aperture) is larger than the transmitting one.

Finally, a mismatch in refractive index profiles (see Figure 5.3(a)) results in a loss which can be shown to be

$$\text{Loss}_{RI} = \begin{cases} -10 \log_{10} \dfrac{\alpha_2(\alpha_1 + 2)}{\alpha_1(\alpha_2 + 2)} \text{ (dB)} & \alpha_2 < \alpha_1 \\ 0 \qquad \text{(dB)} & \alpha_2 \geq \alpha_1 \end{cases}$$

where α_1 and α_2 are the profile parameters for the transmitting and receiving fibers respectively

The intrinsic losses obtained at multimode fiber–fiber joints provided by Eqs to can be combined into a single expression as follows:

$$\text{Loss}_{\text{int}} = \begin{cases} -10 \log_{10} \dfrac{(a_2 NA_2)^2(\alpha_1 + 2)\alpha_2}{(a_1 NA_1)^2(\alpha_2 + 2)\alpha_1} \text{ (dB)} & a_2 > a_1,\ NA_2 > NA_1,\ \alpha_2 > \alpha_1 \\ 0 \qquad \text{(dB)} & a_2 \leq a_1,\ NA_2 \leq NA_1,\ \alpha_2 \leq \alpha_1 \end{cases}$$

Single-mode fiber joints

Loss in Single-mode fiber joints

- Misalignment losses at connections in single-mode fibers have been theoretically considered by Marcuse and Gambling.
- The theoretical analysis which was instigated by Marcuse is based upon the Gaussian or near-Gaussian shape of the modes propagating in single-mode fibers regardless of the fiber type (i.e. step index or graded index).

$$T_1 = 2.17\left(\frac{y}{\omega}\right)^2 \text{dB}$$

- In the absence of angular misalignment Gambling et al. calculated that the loss Tl due to lateral offset y was given by:

$$\omega = a\,\frac{(0.65 + 1.62V^{-\frac{3}{2}} + 2.88V^{-6})}{2^{\frac{1}{2}}}$$

where ω is the normalized spot size of the fundamental mode.*

- However, the normalized spot size for the LP_{01} mode (which corresponds to the HE mode) may be obtained from the empirical formula

$$\omega = a\frac{(0.65 + 1.62V^{-\frac{3}{2}} + 2.88V^{-6})}{2^{\frac{1}{2}}}$$

- where ω is the spot size in μm, a is the fiber core radius and V is the normalized frequency for the fiber. Alternatively, the insertion loss Ta caused by an angular misalignment θ (in radians) at a joint in a single-mode fiber may be given by:

$$T_a = 2.17\left(\frac{\theta\omega\, n_1 V}{aNA}\right)^2 \text{dB}$$

where n1 is the fiber core refractive index and NA is the numerical aperture of the fiber.

A single-mode fiber has the following parameters:

normalized frequency (V) = 2.40
core refractive index (n_1) = 1.46
core diameter ($2a$) = 8 μm
numerical aperture (NA) = 0.1

Estimate the total insertion loss of a fiber joint with a lateral misalignment of 1 μm and an angular misalignment of 1°.

Solution: Initially it is necessary to determine the normalized spot size in the fiber. This may be obtained from Eq. (5.15) where:

$$\omega = a\frac{(0.65 + 1.62V^{-\frac{3}{2}} + 2.88V^{-6})}{2^{\frac{1}{2}}}$$

$$= 4\,\frac{(0.65 + 1.62(2.4)^{-1.5} + 2.88(2.4)^{-6})}{2^{\frac{1}{2}}}$$

$$= 3.12\ \mu\text{m}$$

The loss due to the lateral offset is given by Eq. (5.14) as:

$$T_1 = 2.17\left(\frac{y}{\omega}\right)^2 = 2.17\left(\frac{1}{3.12}\right)^2$$
$$= 0.22 \text{ dB}$$

The loss due to angular misalignment may be obtained from Eq. (5.16) where

$$T_a = 2.17\left(\frac{\theta\omega\, n_1 V}{aNA}\right)^2$$
$$= 2.17\left(\frac{(\pi/180) \times 3.12 \times 1.46 \times 2.4}{4 \times 0.1}\right)$$
$$= 0.49 \text{ dB}$$

Hence, the total insertion loss is:

$$T_T \simeq T_1 + T_a = 0.22 + 0.49$$
$$= 0.71 \text{ dB}$$

Assuming that no losses are present due to the extrinsic factors, the intrinsic coupling loss is given by

$$\text{Loss}_{\text{int}} = -10 \log_{10}\left[4\left(\frac{\omega_{02}}{\omega_{01}} + \frac{\omega_{01}}{\omega_{02}}\right)^{-2}\right] (\text{dB})$$

where ω01 and ω02 are the spot sizes of the transmitting and receiving fibers respectively. Equation (5.17) therefore enables the additional coupling loss resulting from mode-field diameter mismatch between two single-mode fibers to be calculated.

Two single-mode fibers with mode-field diameters of 9.2 μm and 8.4 μm are to be connected together. Assuming no extrinsic losses, determine the loss at the connection due to the mode-field diameter mismatch.

Solution: The intrinsic loss is obtained using Eq. (5.17) where:

$$
\begin{aligned}
\text{Loss}_{\text{int}} &= -10 \log_{10}\left[4\left(\frac{\omega_{02}}{\omega_{01}}+\frac{\omega_{01}}{\omega_{02}}\right)^{-2}\right] \\
&= -10 \log_{10}\left[4\left(\frac{4.2}{5.6}+\frac{5.6}{4.2}\right)^{-2}\right] \\
&= -10 \log_{10} 0.922 \\
&= 0.35 \text{ dB}
\end{aligned}
$$