Fiber Optic Communication

Couplers and Connectors

Lecture 17

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Couplers and connectors

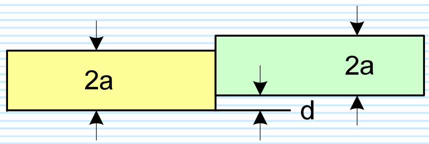
- Connectors:
  - Metallic system: Wire: Soldering: Lossless: Economical
  - Fiber system: fiber: Splicing: Loss: Economical
- Splicing is the permanent connection of two optical fiber.
- Two mechanism of splicing:
  - Fusion
  - Mechanical
- Splices are of two types:
  - Midspan: the connecting of two cables
  - Pigtail: assembly of a fiber that has been factory-installed into a connector in one end, with the other end free for splicing to a cable.
- The quality of splicing is measured by the insertion and reflection losses caused by the splice

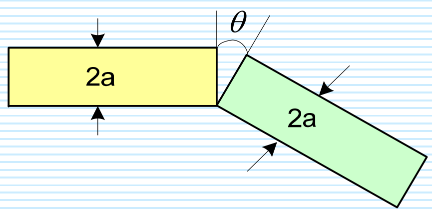
Couplers and connectors losses

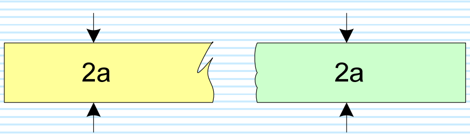
- Connectors losses at any splice stem from the fact that no all light from one fiber is transmitted to another. The loss results from:
  - Mismatch: due to fiber's mechanical dimensions and numerical aperture. An improvement in splicing technique can not solve the problem. Also called intrinsic connection losses.
  - Misalignment: are caused by some imperfection in splicing, that theoretically can be eliminated. An improvement in splicing technique can solve the problem. Also called extrinsic connection losses.
- Misalignment Losses in fiber-to-fiber:
  - Core misalignment and imperfections.
  - Lateral (axial) misalignment
  - Angular misalignment
  - gap between ends contact
  - Non-flat ends
  - Cladding alignment

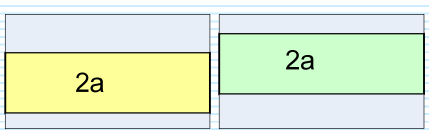
Couplers and connectors losses

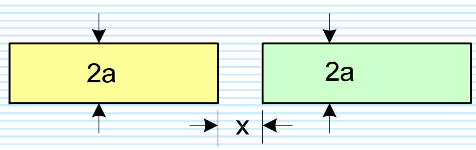
- Misalignment Losses in fiber-to-fiber due to some imperfection in splicing:
  - Core misalignment and imperfections.
  - Lateral (axial) misalignment
  - Angular misalignment
  - gap between ends contact
  - Non-flat ends due to cleaving
  - Cladding alignment





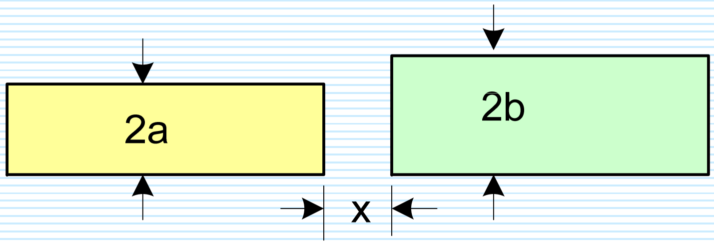






Mismatch losses

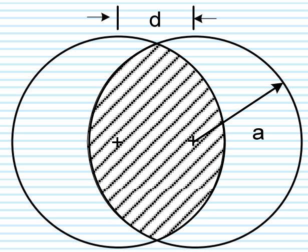
- Coupling efficiency reduction due to mismatch:
  - Different numerical aperture
  - Different core diameter
  - Elliptical cross sections (rather than Circular) with cross section are attached with their major axes unaligned.
  - The core is not centered in the cladding and the outside cladding is used as the reference for aligning the Joint.
  - The distance between the excitation point and the connector (due to unknown distribution of power across the fiber end face, excitation method)
  - Length of fiber following the Junctions.



- Reasonable loss of 0.1 dB for splices
- Reasonable loss of reusable connectors with losses less then 1 dB.

Losses due to lateral misalignment

- Assumptions:
  - Uniform power distribution over the fiber core (suitable for multimode step index fiber).
  - The lateral misalignment loss is due only to the non-overlap of transmission and receiving cores.



- The coupling efficiency η is defined as the ratio of the overlapping area to the core area.

$$\eta = \frac{2}{\pi}\left\{\cos^{-1}\frac{d}{2a} - \frac{d}{2a}\sqrt{\left[1-\left(\frac{d}{2a}\right)^2\right]}\right\}$$

- The inversed cosine is calculated in radians. The loss in dB is:

$$L = -10\log_{10}\eta$$

Losses due to lateral misalignment

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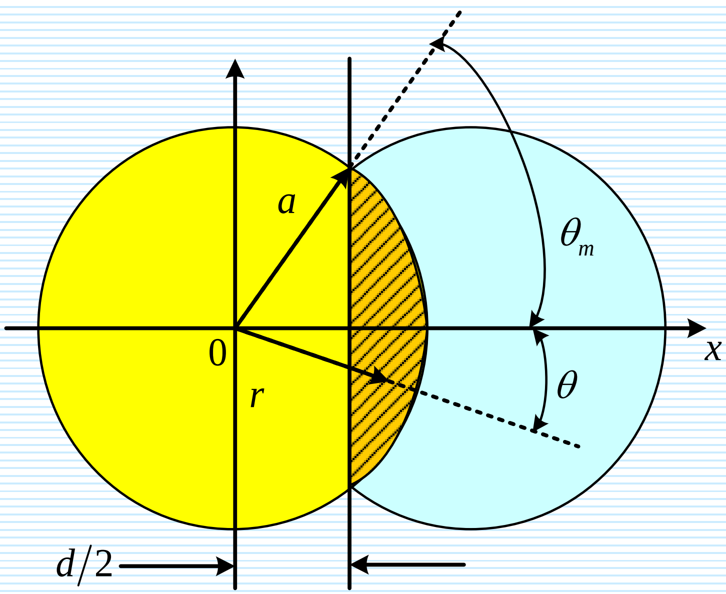


$$\cos\theta = \frac{d/2}{r}$$

$$\cos\theta_m = \frac{d/2}{a}$$

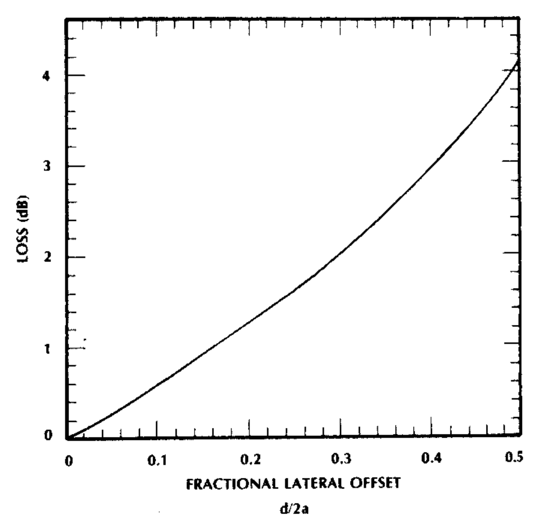
$$\theta_m = \cos^{-1}\frac{d/2}{a}$$

Losses due to lateral misalignment

- The small displacements $d/2a < 0.2$ the equation:

$$\eta = \frac{2}{\pi}\left\{\cos^{-1}\frac{d}{2a} - \frac{d}{2a}\sqrt{\left[1-\left(\frac{d}{2a}\right)^2\right]}\right\}$$

- Reduces to: $$\eta = 1 - \frac{2d}{\pi a}$$
- Lateral misalignment loss for a multimode SI fiber



Axial displacement loss example

- A fiber has a core diameter of $50\mu m$.
  - 1) what is the allowable axial displacement if the coupling loss is to be less than 1 dB.
  - 2) Repeat for losses of 0.5 dB.
  - 3) Repeat for losses of 0.1 dB.
- Solution:
  - The coupling efficiency

$$L = -10\log_{10}\eta \quad \Rightarrow \quad \eta = 10^{-\frac{L}{10}}$$

  - The d/a

$$\eta = \frac{2}{\pi}\left\{\cos^{-1}\frac{d}{2a} - \frac{d}{2a}\sqrt{\left[1-\left(\frac{d}{2a}\right)^2\right]}\right\}$$

- The displacement

Axial displacement loss example

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$$L = -10\log_{10}\eta \quad \Rightarrow \quad \eta = 10^{-\frac{L}{10}}$$

- The displacement

$$\eta = \frac{2}{\pi}\left\{\cos^{-1}\frac{d}{2a} - \frac{d}{2a}\sqrt{\left[1-\left(\frac{d}{2a}\right)^2\right]}\right\}$$

Loss (dB)	$d/2a$	$d\,(\mu m)$
1.0	0.16	8
0.5	0.09	4.5
0.1	0.02	1

Losses due to lateral misalignment

- Higher-ordered modes are more heavily attenuated than lower modes.
- Higher-ordered modes contained more power near the core-cladding interface.
- The power density at the end of a long fiber will be lower at the edge of the core than at points near its center.
- For small axial displacements, only the edges of the transmitting core miss the receiving fiber but the edge contain less power than is assumed in

$$L = -10\log_{10}\eta$$

- The actual loss is less than that predicted by theory.

Losses due to lateral misalignment

- Multimode Graded-index fiber (GRIN) numerical aperture varies across the face of the core.
- The numerical aperture has

$$NA = n_1\sqrt{2\Delta}\sqrt{1-\left(\frac{r}{a}\right)^2}$$

- The numerical apertures of transmitter and receiver match at every point within the core when the two fibers meet with no offset.
- With an offset, there is a NA mismatch at nearly every point.
- At those points where the receiver NA is larger than the transmitter NA, all the power is transferred.
- At those points where the receiver NA is less than the transmitter NA, some of the power is lost.

Losses due to lateral misalignment

- The fractional efficiency at those points is equal to the ratio of square of the local numerical aperture.
- The coupling efficiency is the average of the local efficiencies weighted according to power distribution across the end face.
- The power distribution across the face is not generally known. This fact discourage comprehensive analysis.
- For both step index (SI) and parabolic-index fibers with the nearly Gaussian beam. The loss between identical fibers:

$$L = -10\log_{10} e^{-\left(\frac{d}{w}\right)^2}$$

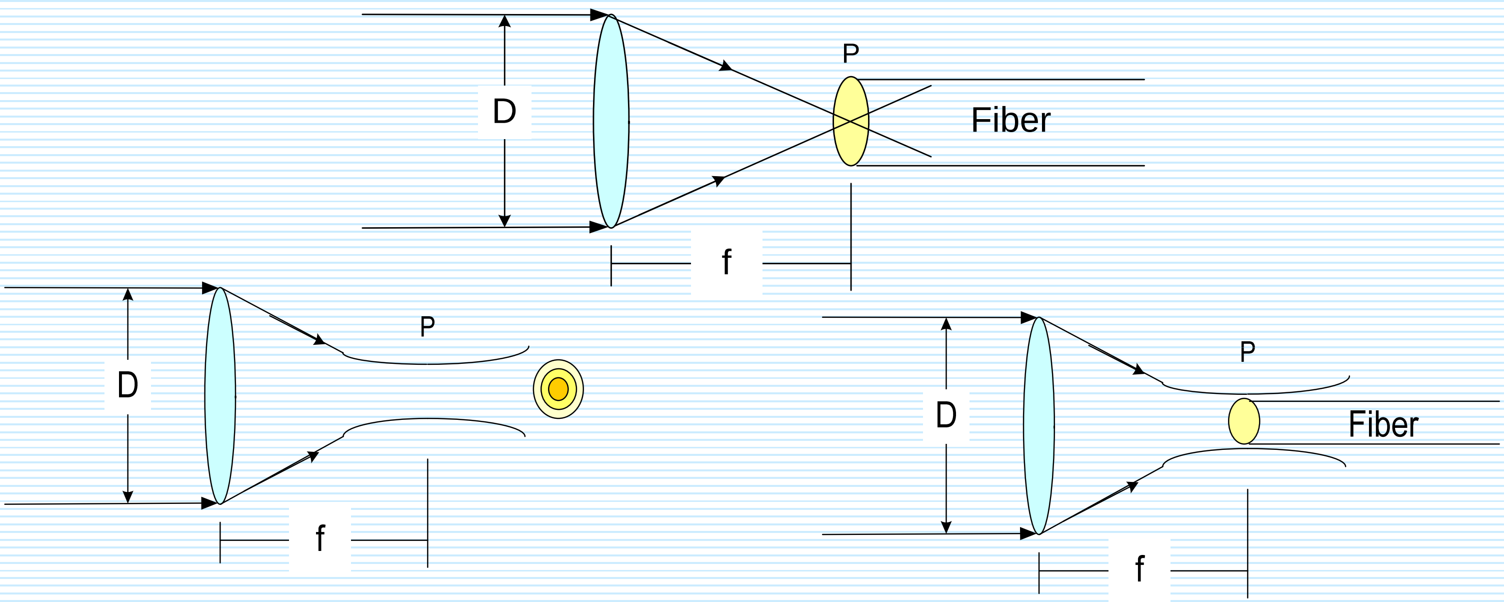
- Where W is the spot size.
- The spot size in the focal plane

$$W_0 = \frac{\lambda f}{\pi W}$$

Physical optics (Diffraction theory) review

- Collimated uniform light beam does not converge to a point but instead reduces to a central spot of light surrounded by rings of a steadily diminishing intensity. The central spot has diameter.

$$d = 2.44\lambda f / D$$

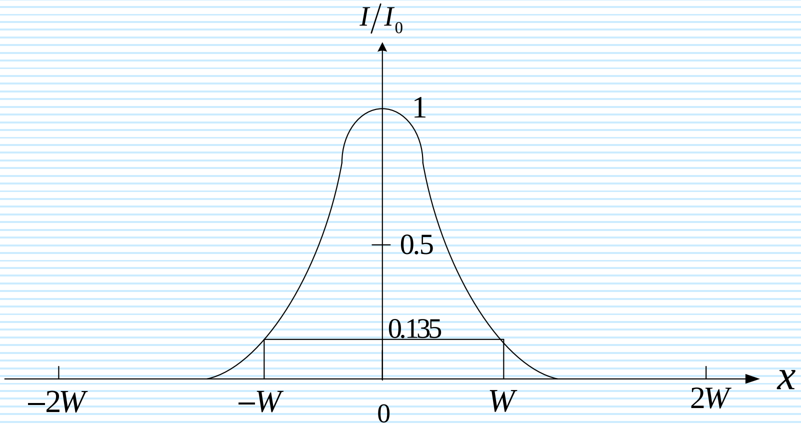


Diffraction theory review

- Very small fibers (having diameters of a few micrometers) and actual light sources produces non-uniform beams. The intensities vary across the transverse plane. A transverse pattern is the Gaussian distribution.
- A Gaussian intensity distribution:

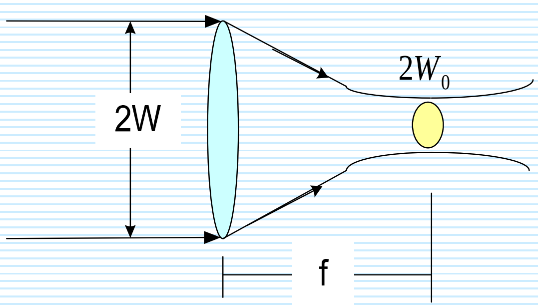
$$I = I_0 e^{-\frac{2x^2}{W^2}} \qquad W_0 = \frac{\lambda f}{\pi W}$$

- A normalized Gaussian intensity distribution:



Diffraction theory review

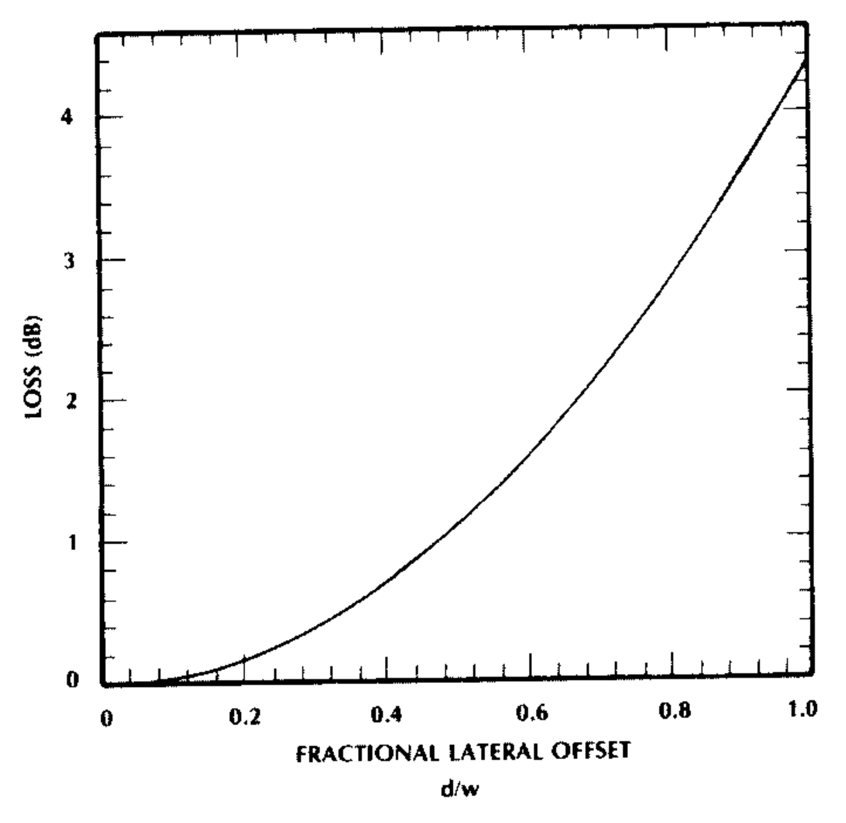
- The Gaussian beam spot pattern appears to be a circle of light. The edges of the circle are not sharp. The light intensity drops gradually from I_0 , the maximum at the center.
- The radius of the spot is the distance at which the beam intensity has dropped to $1/e^2 = 0.135$ times its peak value I_0 . This radius is called the spot size.
- Focusing a Gaussian light with a lens yields distribution of light in the focal plane that is also Gaussian shaped. There are no surrounding rings like those that appear when focusing a uniform beam. The spot size in the focal plane is:



$$W_0 = \frac{\lambda f}{\pi W}$$

Losses due to lateral misalignment

- The small displacements $d/2a < 0.2$the equation:



Lateral misalignment loss example

- Consider the single-mode fiber core diameter of $50\mu m$. Plot the coupling loss as a function of lateral misalignment at the wavelengths $1.3\mu m$ and $1.55\mu m$, Do this for offset from $0\, to\, 5\mu m$.
- Solution: The V parameters must be calculated at two wavelengths of interest.

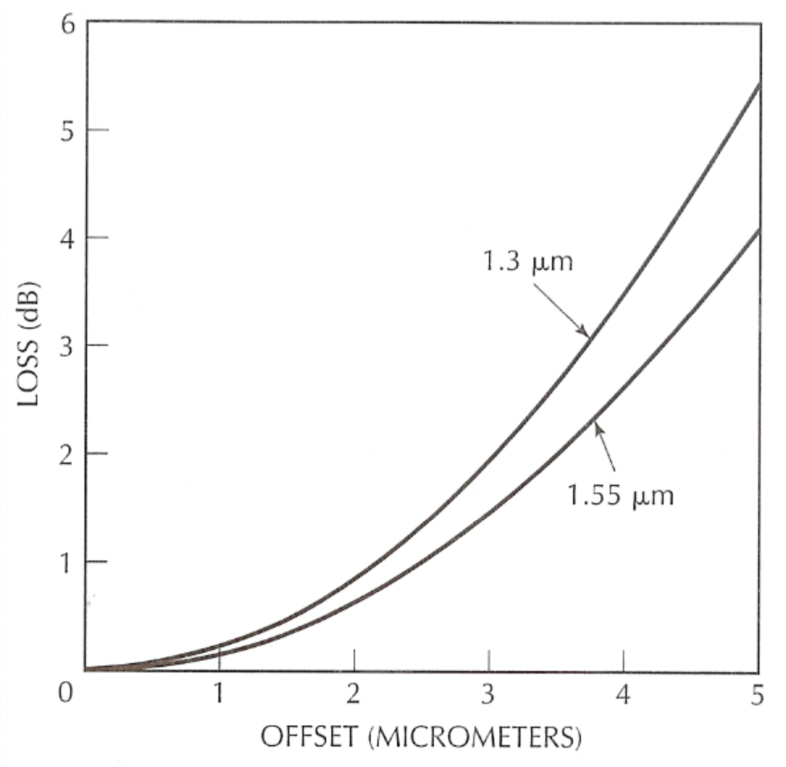
$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$$

$$\frac{W}{a} = 0.65 + 1.619V^{-\frac{3}{2}} + 2.879V^{-6}$$

$\lambda(\mu m)$	V	W/a	$W(\mu m)$
1.3	2.31	1.13	4.47
1.55	1.94	1.3	5.16

Lateral misalignment loss plot example

- Plot of the coupling loss as a function of lateral misalignment at the wavelengths $1.3\mu m$ and $1.55\mu m$



Angular misalignment

- The coupling efficiency due to small angular misalignment of multimode SI fibers is:

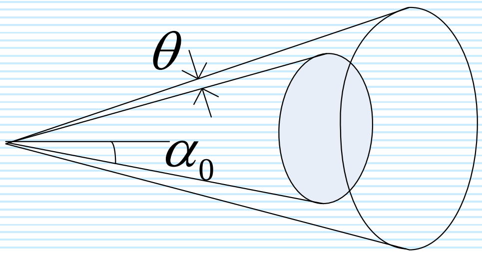
$$\eta = 1 - \frac{n_0 \theta}{\pi NA}$$

- Where n_0 is the refractive index of the material filling the grove formed by the two fibers and θ is the misalignment angle in radian. The loss is:

$$L = -10\log_{10}\left(1 - \frac{n_0 \theta}{\pi NA}\right)$$

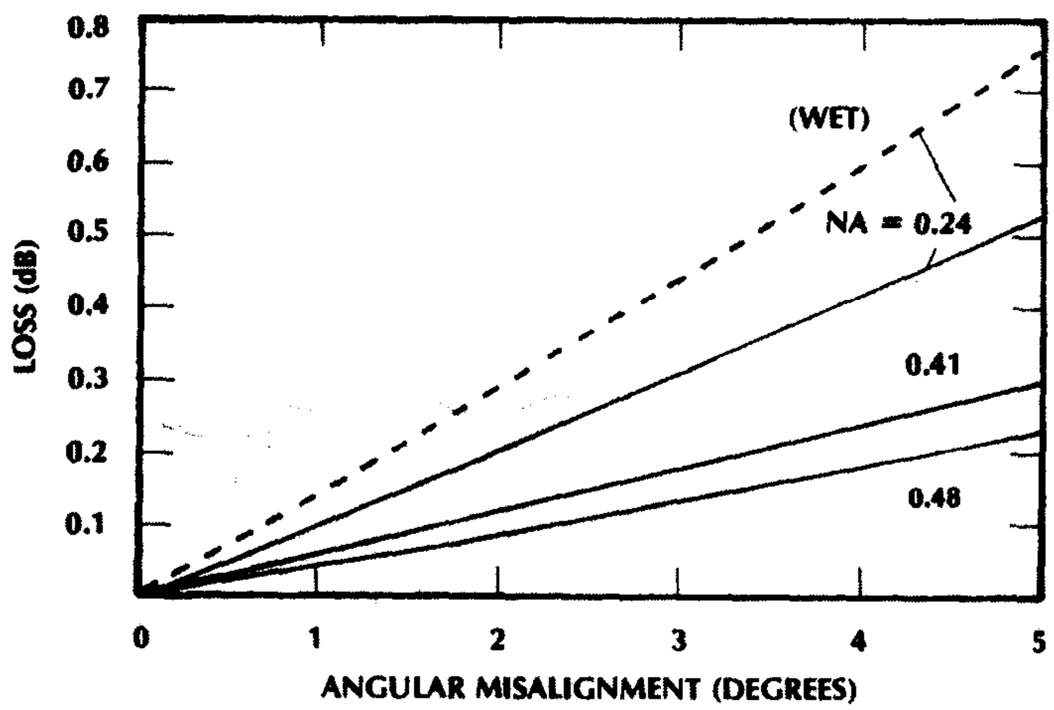
- The efficiency was found by computing the overlap of the transmitting and receiving cones, assuming uniform power distribution.

- Where θ is tilt angle and $NA = n_0 \sin \alpha_0$



Angular misalignment plot

- Plot of the coupling efficiency due to small angular misalignment of multimode SI fibers per degree is:

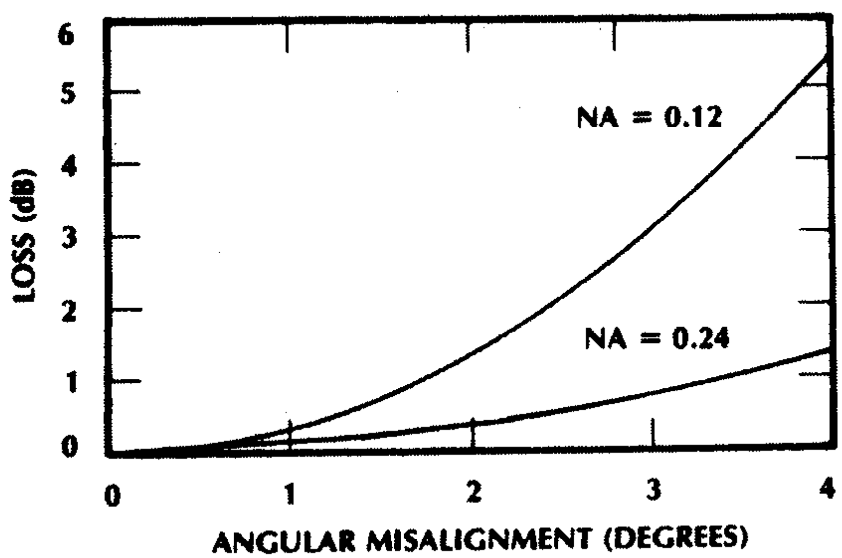


Angular misalignment

- Angular misalignment losses for single-mode fiber:

$$L = -10\log_{10} e^{-\left(\frac{\pi n_2 w\theta}{\lambda}\right)^2}$$

- The coupling efficiency due to small angular misalignment of single SI fibers is:



example

- A SI fiber $n_1 = 1.465, n_2 = 1.46$ and normalized frequency 2.4.
  - 1) Compute its numerical aperture and core radius at $0.8\mu m$.
  - 2) The spot size at $0.8\mu m$.
- Solution:
  - 1) the numerical aperture

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.465)^2 - (1.46)^2} = 0.12$$

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \Rightarrow a = \frac{\lambda V}{2\pi\sqrt{n_1^2 - n_2^2}} = \frac{0.8(2.4)}{2\pi(0.12)} = 2.53\mu m$$

  - 2) The spot size at $0.8\mu m$.

$$\frac{w}{a} = 0.65 + 1.619V^{-\frac{3}{2}} + 2.879V^{-6} = 0.65 + 1.619(2.4)^{-\frac{3}{2}} + 2.879(2.4)^{-6} = 1.1$$

$$w = 1.1(2.53) = 2.78\mu m$$

End separation loss

- Losses due to gap between the fibers being joined has two components:
  - 1) Two boundaries between the fiber medium and air:

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 = \left(\frac{1 - 1.5}{1 + 1.5} \right)^2 = 0.04$$

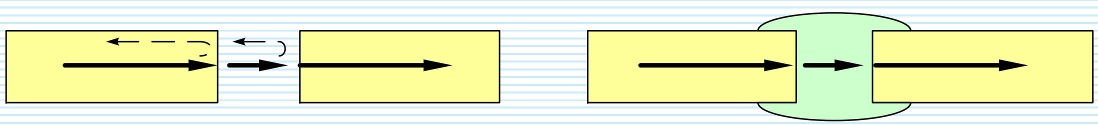
- 4% of light reflected. 96% transmitted. Loss in dB.

$$L = -10 \log_{10} 0.96 = 0.177 \; dB$$

- The total loss

$$L = 2 \times 0.177 \; dB = 0.35$$

- To improve the loss: fill the gap by the index-matching fluid.

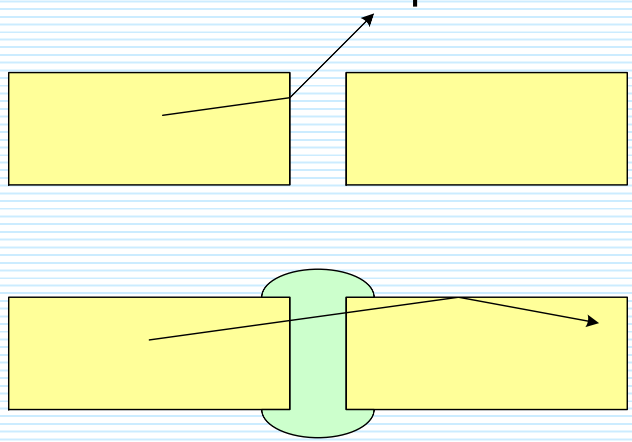


End separation loss

- Losses due to gap between the fibers being joined has two components:
  - 2) some transmitted ray are not intercepted by receiving fiber:

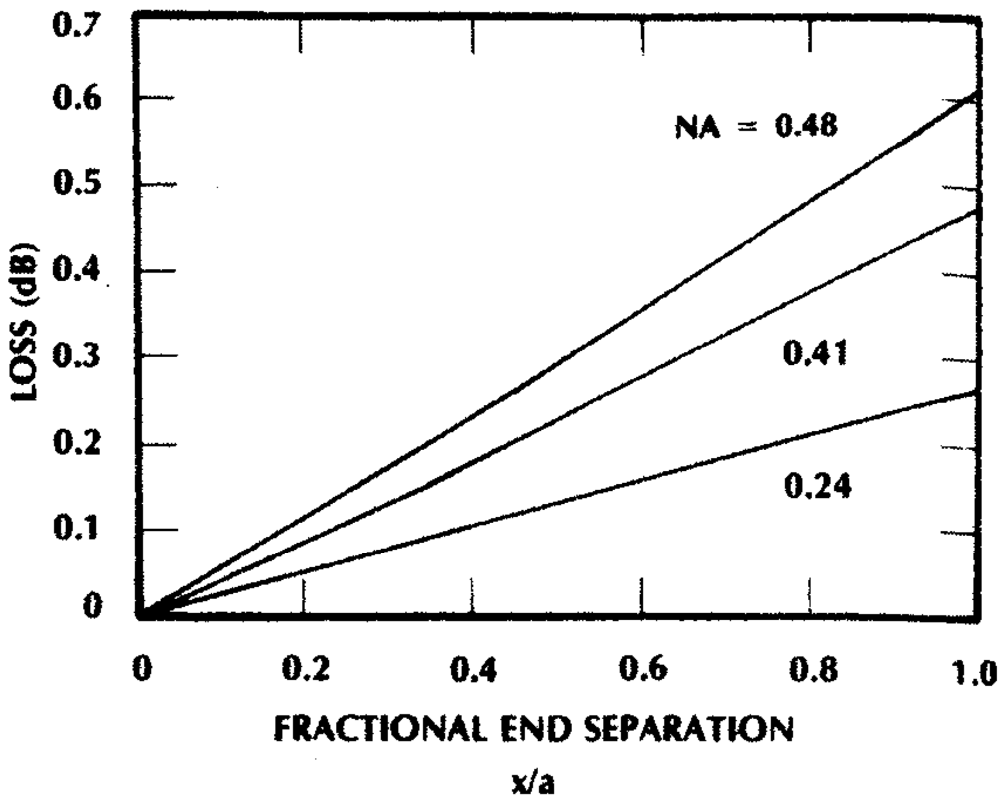
$$L = -10\log_{10}\left(1 - \frac{xNA}{4\,a\,n_0}\right)$$

- Where n_0 is the refractive index of matching fluid. An index-matching fluid decreases fiber-separation loss by reducing beam divergence



End separation loss for multimode fiber

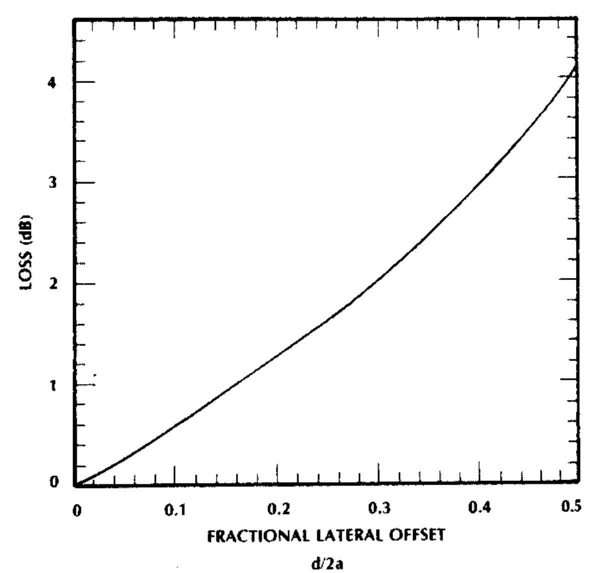
- End separation for a multimode SI fiber: $L = -10\log_{10}\left(1 - \frac{xNA}{4 a n_0}\right)$



Example

- Estimate the allowed misalignment for a multimode SI fiber if each type of error is allowed to contribute 0.25 dB of loss. The core radius is $50\mu m$ and $NA = 0.24$
  - 1) lateral offset: L=0.25 from the figure d/2a=0.045.

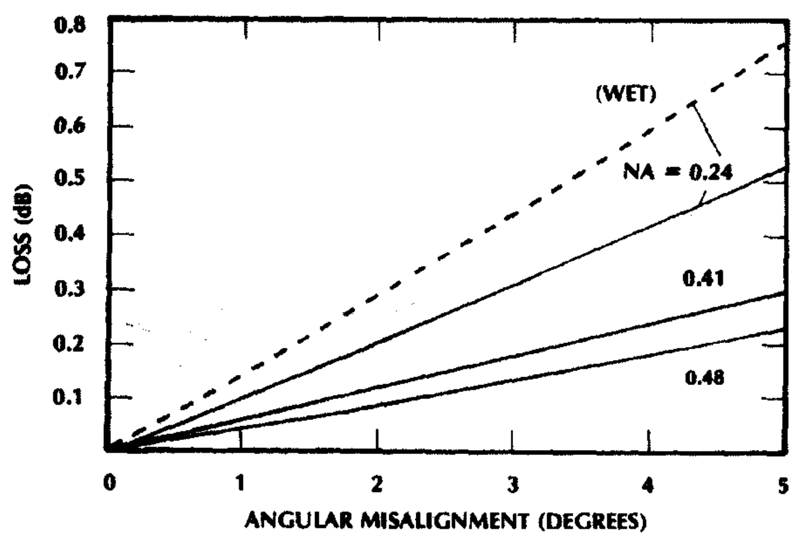
$$L = 0.045\left(2 \times 50\mu m\right) = 4.5\mu m$$



Example

- Estimate the allowed misalignment for a multimode SI fiber if each type of error is allowed to contribute 0.25 dB of loss. The core radius is $50\mu m$ and $NA = 0.24$
  - 2) angular misalignment: from the figure, the angle is 2.4 degrees.

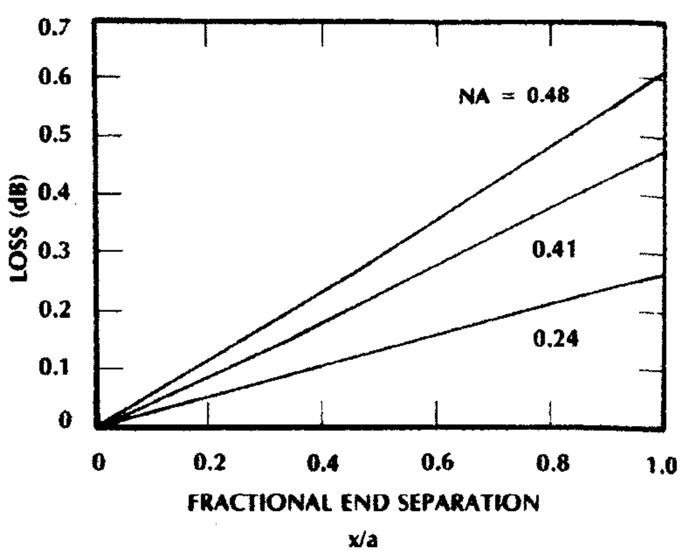
$$L = 0.045(2 \times 50\mu m) = 4.5\mu m$$



Example

- Estimate the allowed misalignment for a multimode SI fiber if each type of error is allowed to contribute 0.25 dB of loss. The core radius is $50\mu m$ and $NA = 0.24$
  - 3) the end separation: from the figure, the $x/a = 0.94$

$$x = 0.94a = 0.94(50\mu m) = 47\mu m$$



The gap loss for single mode fibers

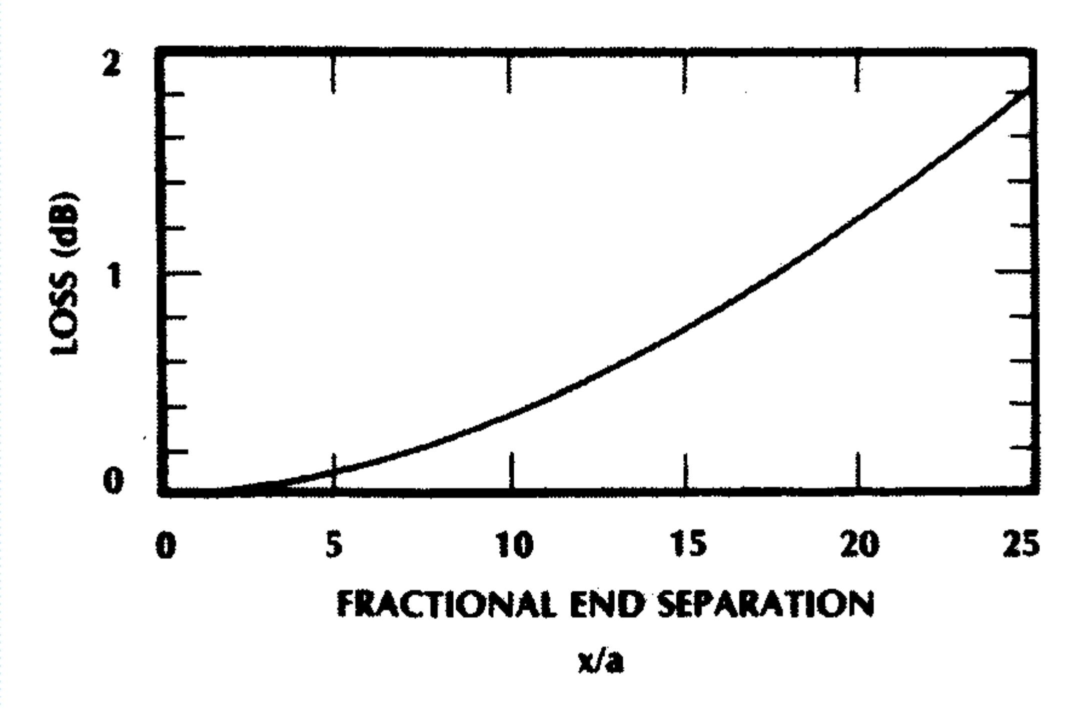
- The gap loss for single mode fibers:

$$L = -10\log_{10} \frac{4\left(4z^2+1\right)}{\left(4z^2+2\right)+4z^2}$$

- Where $z = \dfrac{x\lambda}{2\pi n_2 w^2}$
- From the next page figure the gap of 10 times of the core radius produces a loss than 0.4 dB.
- Axial misalignment is potentially the most serious problem in multimode SI fiber.

Gap loss for single-mode fiber

- The gap loss for single-mode fiber is:



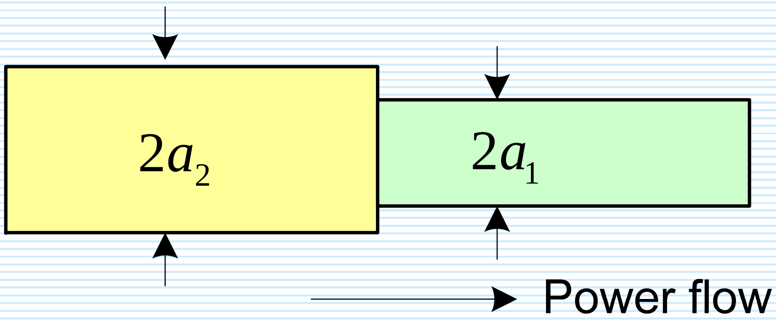
- End- separation loss for single mode SI fiber V=2.4, w/a=1.1,NA=0.12and $\lambda = 0.8\mu m$

Loss due to fiber core radius difference

- The loss transmitting from a fiber of core radius a_1 to one having core radius a_2 is:

$$L = -10\log_{10}\left(\frac{a_2}{a_1}\right)^2$$

- Applicable for both SI and GRIN fibers. If all the allowed modes are equally excited
- If the receiving fiber core is larger than the transmitting one $a_1 > a_2$ there is no loss.

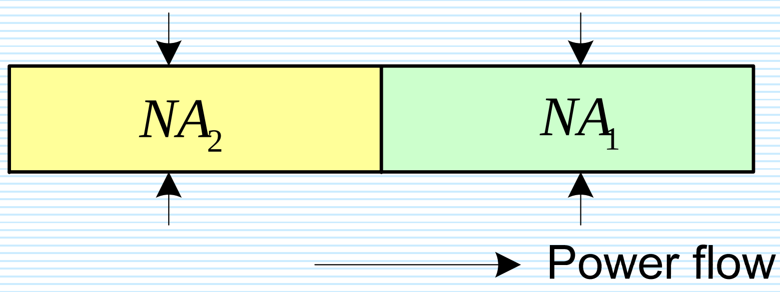


Loss due to fiber core radius difference

- The loss transmitting from a fiber with a higher numerical aperture to lower one is:

$$L = -10\log_{10}\left(\frac{NA_2}{NA_1}\right)^2$$

- Applicable for both multimode SI and GRIN fibers. If all the allowed modes are equally excited
- If the receiving fiber NA is larger than the transmitting one $NA_1 > NA_2$ there is no loss.



Reference

- Joseph C. Palais, *Fiber optic communication.* fifth edition, Pearson, Prentice Hall. 2005.