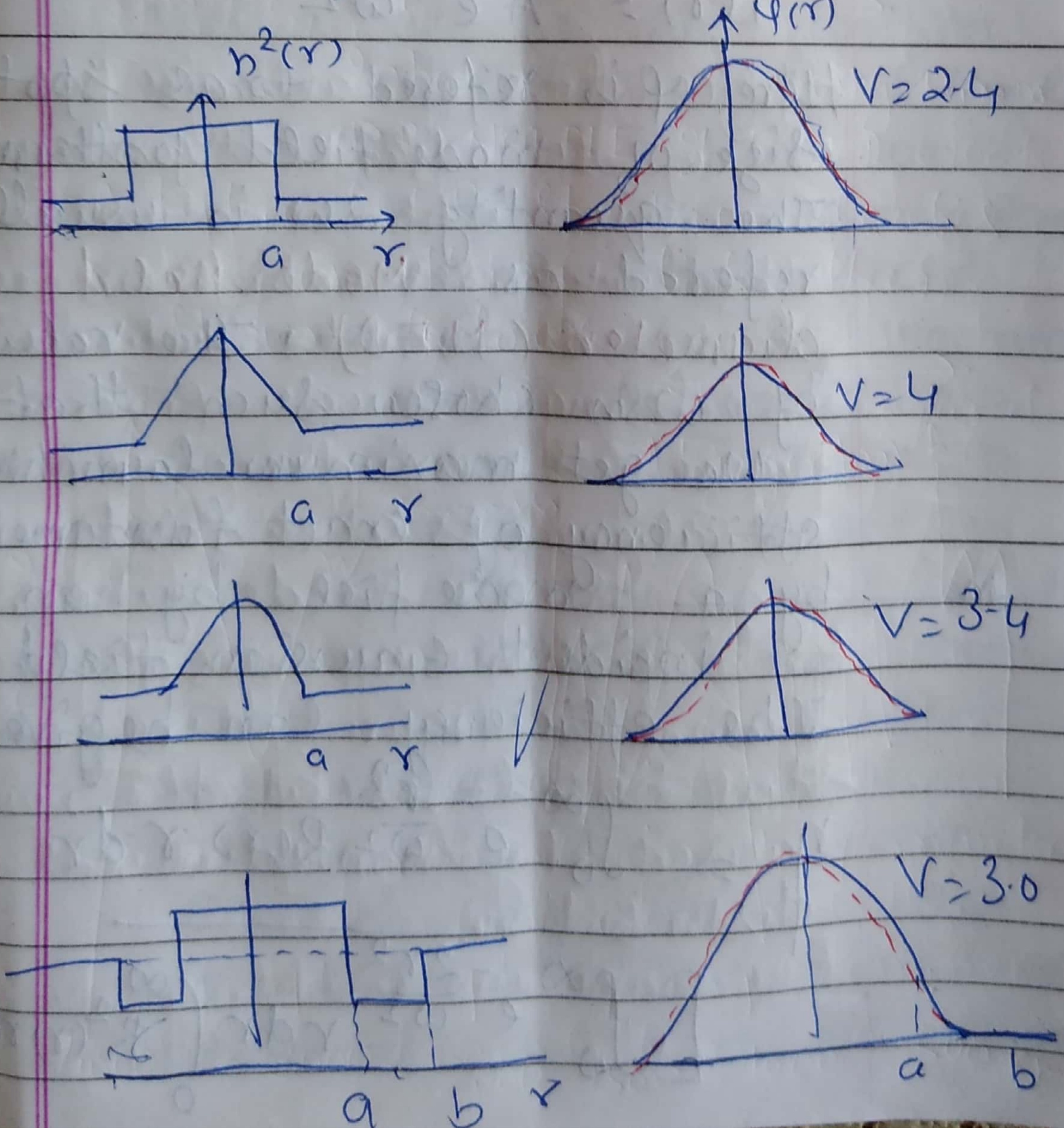
Gaussian approximation for Single Mode Fiber :- The fundamental mode field distribution for a single mode fiber is very important characterstics that determines various important parameters like launching efficiencies, Bending loss and so forth. Figure shows some typical Refractive index profile of single mode fiber and their corresponding fundamental mode field distribution



In this figure solid black lines represent exact field variation and dashed red lines represent best fitted Gaussian function. It can be seen that irrespective of refractive index profile, the fundamental mode field distribution can be well approximated by Gaussian function which can be given in form

$$\psi(r) = A e^{-\frac{r^2}{w^2}}$$

Here ψ is refered to as spot size of mode field pattern. The quantity $2w$ is usually refered as Mode field diameter (MFD). The value of w is chosen such that we get maximum launching efficiency of exact fundamental by ~~a~~ mode field by an incident Gaussian field. The efficiency can be given as

$$\eta = \frac{\int_0^\infty e^{-\frac{r^2}{w^2}} R(r)\, r\, dr}{\left[\int_0^\infty e^{-\frac{2r^2}{w^2}} r\, dr \int_0^\infty R^2(r)\, r\, dr\right]^{1/2}}$$

Here $R(r)$ represents exact modal field. For step index fiber $R(r)$ can be expressed in terms of Bessel function. The expression for w is

$$\frac{w}{a} \simeq \left(.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6}\right)$$

The value of V is $.8 < V < 2.5$

$a \rightarrow$ Core Radius

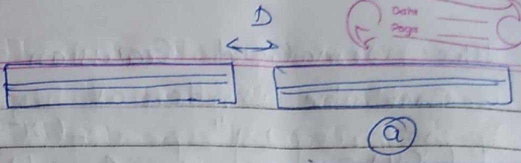
The above formula gives a value of w to within about 1%. For typical single mode fiber $n_1 = 1.454$ and $n_2 = 1.45$, $a = 4.46\ \mu m$ operating at 1300 nm the mode field diameter is 10 µm. At 1500 nm the same fiber would have field diameter is about 11.2 µm assuming same n_1 and n_2. From equation we can see that two non identical single mode fibers can have same spot size at given wavelength. Therefore a single mode fiber having $V = 2.2$ and $a = 4.27\ \mu m$ has also field diameter of 10 µm at 1300 nm

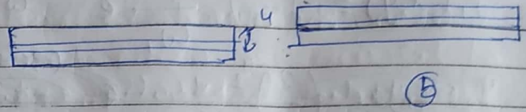
Splice Loss:- Splice loss refers to the part of optical power that is not transmitted through the splice and is radiated out of the fiber. The total loss in decibels at the fusion splice is given

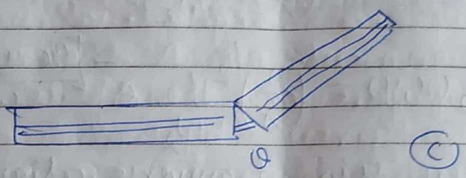
$$\alpha_{splice} = 10 \log_{10} \frac{P_{input}}{P_{transmitted}}$$

since $P_{in} > P_{trans}$. therefore

Splice loss is always positive. One of the great advantage of Gaussian approximation is that it gives expression for losses at joints between two single mode fibers. Figure shows three common misalignments at a joint between two single mode fibers. Even if none of misalignments shown in figure, there will still be losses at the joints caused by non identical field distribution.







In general total loss in the simultaneous presence of more than one misalignment is not the sum of individual misalignment losses. The three types of misalignment are possible

ⓐ Transverse Misalignment
(b) Longitudinal "
(C) Angular "

Ⓐ **Loss due to Transverse misalignment** - Consider transverse misalignment of two single mode fibers that are represented by Gaussian modes with spot size w_1 and w_2. Let the direction of misalignment to be along x axis

The normalised Gaussian modes can be written as

$$\varphi_1(x,y) = \left(\frac{2}{\pi}\right)^{1/2} \frac{1}{\omega_1} e^{-\frac{(x^2+y^2)}{\omega_1^2}}$$

~~$\varphi_2(x,y) = \left(\frac{2}{\pi}\right)^{1/2} \frac{1}{\omega_2} e^{\frac{(x^2+y^2)}{\omega_2^2}}$~~

$$\varphi_2(x,y) = \left(\frac{2}{\pi}\right)^{1/2} \frac{1}{\omega_2} e^{-\frac{[(x-u)^2+y^2]}{\omega_2^2}}$$

Here u is transverse alignment shown in figure (b).

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \varphi_{1,2}^2 \, dx\, dx = 1$$

Fractional power that is coupled to fundamental mode

$$T = \left| \int_{-\infty}^{\infty} \varphi_1 \varphi_2^{x} \, dx\, dy \right|^2$$

Solving this we get

$$T = \left(\frac{2\omega_1\omega_2}{\omega_1^2+\omega_2^2}\right)^2 \exp\left[-\frac{2u^2}{(\omega_1^2+\omega_2^2)}\right]$$

For maximum coupling power at $u = 0$

$$T_{max} = \left(\frac{2\omega_1\omega_2}{\omega_1^2+\omega_2^2}\right)^2$$

Loss is given by

$$\alpha(dB) = -20 \log \left(\frac{2\omega_1\omega_2}{\omega_1^2+\omega_2^2}\right)$$

For Identical fibers $\omega_1 = \omega_2$

$$T_{max} = 1$$

This type of loss will be less than $\cdot 1$ dB provided

$$\cdot 86 < \frac{\omega_1}{\omega_2} < 1 \cdot 16$$

For identical fibers the loss in decibels is given by

$$\boxed{\alpha(dB) = 4 \cdot 34 \left(\frac{u}{\omega}\right)^2}$$

(B) **Angular misalignment**: For an angular misalignment of θ shown in figure (c) between the axis of two single mode fibers with spot size ω, the loss is given by

$$\alpha_a(dB) = 4 \cdot 34 \left(\frac{\pi n_1 \omega \theta}{\lambda_0}\right)^2$$

Here n_1 is refractive index of medium between fiber ends. λ_0 is free space wavelength. θ is measured in radians.

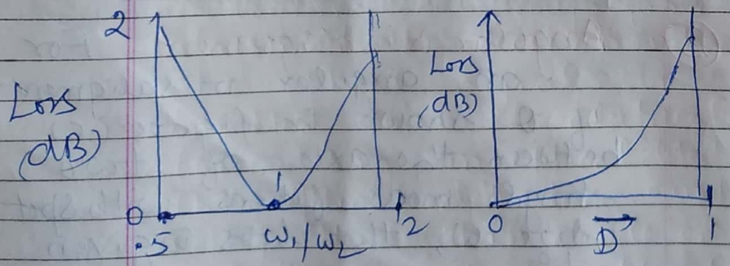
(C) **Longitudinal Misaligment:** For a longitudinal mis-alignment of D shown in figure ⓐ, the splice loss is given by

$$\alpha_l = 10 \log (1+\bar{D}^2)$$

Here $\bar{D} = \dfrac{D \lambda_0}{2\pi n_1 w^2}$

$\alpha_l = .06\,dB$

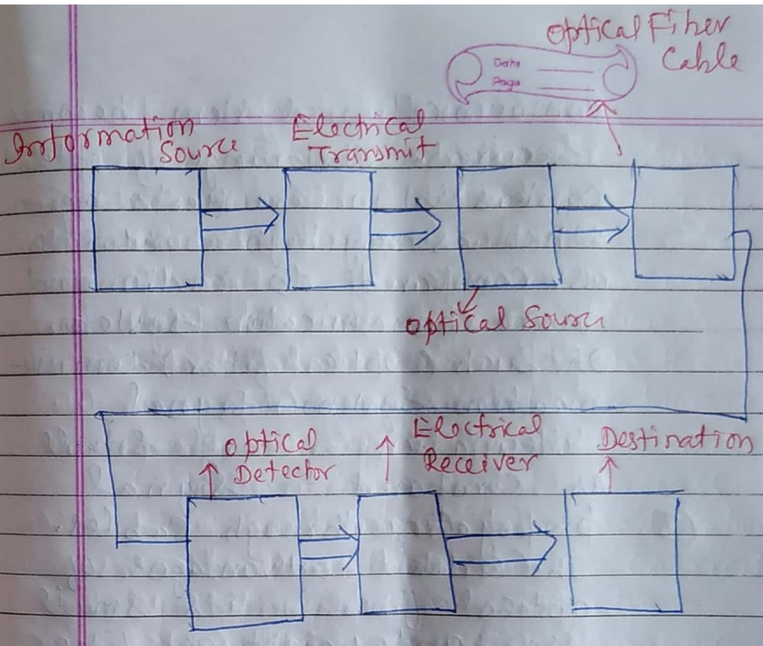
It is not majoar sourceg Loss



Optical Fiber Communication System:

Communication is transferring of information from one place to other. To communicate over a long distance communication systems are required. In these communications, information is being transferred over the wide distance range by the process of modulation. In modulation process information is carried by high frequency electro-magnetic wave. These waves are called carrier wave. In optical fiber communication system, the visible optical carrier waves are required. These waves are of high frequencies of around 100 Tera Hertz.

In 1970 fiber optic Communications revolutionized with the invention of Laser diodes. In 1975 first commercial fiber optic communication system was developed which used semiconductor laser as optical source at a wavelength of ·8 um. Then in 1980 Commercially multi mode fibers was operated at 1·3 um by using Laser diode as optical source. Figure shows the block diagram of optical fiber communication system. The information is transmitted in digital or analog form. The information at the source is in electrical form. At the optical source electrical signal is converted into optical signal. The optical source at the transmitter side can be laser diode or an LED. Now optical signal is transmitted through fiber (glass). At the receiver end, the optical signal is Converted back to electrical form using an optical detector The optical detector can be a pn diode, pin diode or avalanche diode. optical detection provides the optical electrical conversio



Block Diagram

In optical fiber communication signal is in optical form and transmitted through the glass fiber. The optical fiber communication system has many advantages over the conventional communication system in which electric signals travell through the copper wires. As the signal travels in optical form and the signal remains confined to glass fiber, optical fiber communication system becomes secured. The range of optical carriers is in Tera Hertz region which as very high bandwidth as compared to radio and micro communication system.

In such (optical fiber) communication system signal attenuation is very small as compared to signal propogating through cables.

The added advantages of optical fiber is its small size and weight as fiber is made up of glass or plastic and diameter of fiber is as small as a single strand of hair.

There are following generations of optical fiber communicatn system

① First generation
② Second "
③ Third Generation
④ Fourth "
⑤ Fifth "
⑥ Sixth Generation

First generation (Graded Index Fibers)

Year Implemented - 1980
Bit Rate - 45 Mb/s
Repeater spacing - 10 Km
operating wavelength - 0.8 μm
Semiconductor - Ga As

In this generation fiber loss at that wavelength was close to 3dB/Km, optical signal needed to be regenerated every 10 Km or so using called repeaters. This may sound like a major limitation but it was better than coaxial cable technology that required regeneration every Kilometer ora so.

② Second Generation (Single Mode Fibers)

Year Implemented - 1985
Bit rate - 100 Mb/second to 1.7 Gb/sec.
Repeater spacing - 50 Km
operating wavelength - 1.3 μm

Semiconductor - Ga As P.

In second generation, the Bit rate was initially limited to 100 Mb/s because of dispersion in multimode fibers. This was overcome by using single mode fibers. In 1981 an experiment demonstrated transmission 2 Gb/s over 44 Km of single mode fiber.

③ Third Generation (Single Mode Lasers)

Year Implemented - 1990
Bit rate - 10 Gb/s
Repeater spacing - 100 Km
Operating wavelength - 1.55 μm

The best performance was achieved using dispersion shifted fibers in combination with lasers oscillating in a single longitudinal mode.

A relatively large repeater spacing reduced the need of regeneration, however economic pressures demanded further increase in its value to 100 Km.

④ Fourth Generation System (Optical Amplifiers)

Year Implemented - 1996
Bit rate - 10 Tb/s
Repeater spacing - >10000 Km

Operating wavelength - 1.45 μm - 1.62 μm

The attentian of system designers shifted toward using three new ideas

(a) Periodic optical amplification for managing fiber losses.

(b) Periodic dispersion compensation for managing fiber dispersion

(c) WDM (Wavelength Divison Multiplexing) technique for enhancing system capacity.

In most WDM systems, fiber losses are compensated periodically by using Erbium doped fiber amplifier spaced 60-80 Km apart.

In 2001, 11 Tb/s experiment in which 273 channels each operating at 40 Gb/s were transmitted over a distance of 117 Km.

⑤ Fifth Generation(Raman Amplification

Year Implemented – 2002
Bit rate – 40Gb/s – 160Gb/s
Repeater spacing – 24000Km – 35000Km
operating wavelength – 1.53um – 1.57um

The focus of fifth generation systems was on making the WDM systems more efficient spectrally. This was accomplished by reviving the Coherent detection scheme that was studied in late 1980 but abandoned soon after fiber based optical amplifiers became available. A new record was set in 2011 when 64 Tb/s Transmission was realized over 320 Km of a single mode fiber using 640 WDM channels.

⑥ Sixth Generation:-

As the Capacity of WDM systems approached 10 Tb/sec indicating that 10 Trillions bit could be transmitted each second over a single piece of optical fiber supporting a single mode (optical) Inside its tiny core. In 2012, experiment SDM (Space Divison Multiplexing) was used to demonstrate data transmission at 1000 Tb/s or (1 Pb/se) by employing a 12core fiber. Each fiber core Carried 222 WDM Channels and each wavelength transmitted a 380 Gb/se bit Stream over a 52 Km long multi core fiber having Spectral efficiency 7.6 bit/s/Hz.

Word wide Fiber optic Communication Network.

The advent of Internet in 1990's made it necessary to develop a world wide network capable of connecting all computer in transparent manner. The first such cable was installed in 1988 across Atlantic ocean but it was designed to operate at only 280 Mb/s by using second generation technology. Such network required deployment of fiber based submarine cables across all oceans.

High capacity Submarine FOS.

System	Year	Capacity (Tb/sec)	Length (Km)
VSNL Transatlantic	2001	2.56	13000
FLAG	2001	4.8	28000
Apollo	2003	3.2	13000
SEA-ME-WE4	2005	1.28	18,800
Asia-American gateway	2009	2.88	20000
India Me-WE	2009	3.84	13000
African Coast to Europe	2012	5.12	13000
West africa Cable	2012	5.12	14500
Arctic Fiber	2015	8.0	18000