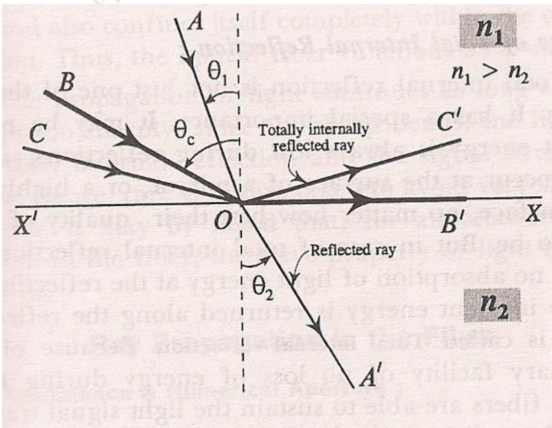
Optical Fibers

1. Total Internal Reflection:

When a ray of light travels from denser to rarer medium it bends away from the normal. As the angle of incidence increases in the denser medium, the angle of refraction also increases. For a particular angle of incidence called the “critical angle”, the refracted ray grazes the surface separating the media or the angle of refraction is equal to 90°. If the angle of incidence is greater than the critical angle, the light ray is reflected back to the same medium. This is called “Total Internal Reflection”.

In total internal reflection, there is no loss of energy. The entire incident ray is reflected back. XX^1 is the surface separating medium of refractive index n_1 and medium of refractive index n_2, $n_1 > n_2$. AO and OA^1 are incident and refracted rays. θ_1 and θ_2 are angle of incidence and angle of refraction, $\theta_2 > \theta_1$. For the ray BO, θ_C is the critical angle. OB^1 is the refracted ray which grazes the interface. The ray CO incident with an angle greater than θ_C is totally reflected back along OC^1.



TOTAL INTERNAL REFLECTION

From Snell’s law, $n_1 \sin\theta_1 = n_2 \sin\theta_2$

For total internal reflection, $\theta_1 = \theta_C$ and $\theta_2 = 90°$

$n_1 \sin\theta_C = n_2$ (because $\sin 90° = 1$)

$\theta_C = \sin^{-1}(n_2/n_1)$

In total internal reflection there is no loss or absorption of light energy. The entire energy is returned along the reflected light. Thus is called Total internal reflection.

2. Advantages of optic fibres over co-axial Cu cable

Sl.No	Optic fibre	Co-axial Cu cable
1	It is made of glass/plastic which is very light and inexpensive	It is made of copper, heavy and expensive
2	Optic fibres carry the information in the form of light pulses, leakage free and absolutely safe	Co-axial cables carry the information in the form of electrical signals, leakages are possible and hence not very safe
3	They are free from radio interference and hence, the reception is much better	They carry the information in the form of electrical pulses which can undergo radio interference. Communication will be noisy
4	They are free from corrosion and other atmospheric effects. Hence, maintenance cost is low	They are vulnerable for corrosion and other atmospheric effects. Hence, periodic replacement is necessary. Maintenance cost will be high
5	They operate in visible range frequency, bandwidth will be larger. Hence, number of channels information will be much greater	They operate in microwave frequency, band width will be less comparatively. Hence, number of channels information will be less

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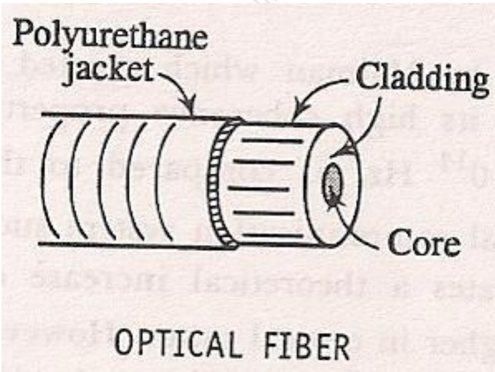
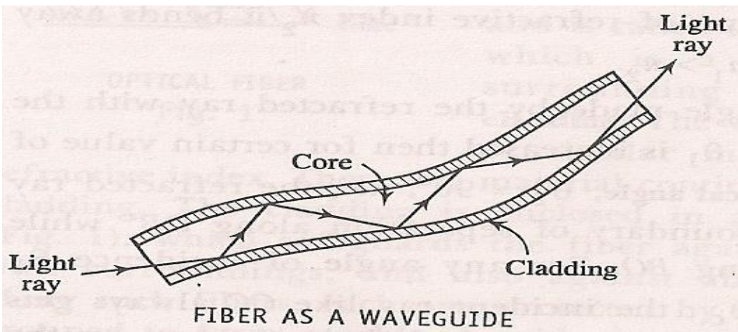
Optical Fibers:

They are used in optical communication. It works on the principle of Total internal reflection (TIR). Optical fiber is made from transparent dielectrics. It is cylindrical in shape. **Structure:** An optic fibre consists of 3 layers. The inner cylindrical part is called as core of refractive index n_1. The outer part is called as cladding of refractive index n_2, $n1>n2$. There is continuity between core and cladding. Cladding is enclosed inside a polyurethane jacket. Number of such fibers is grouped to form a cable. The function of core is to carry the information in the form of optical pulses and the cladding supports total internal reflection. The function of jacket is to provide mechanical strength to the fibre.



OPTICAL FIBER

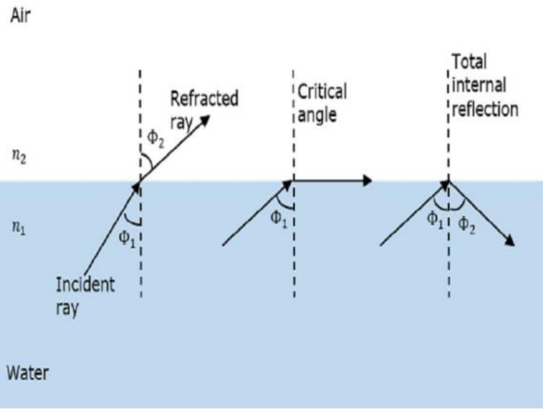
The light entering through one end of core strikes the interface of the core and cladding with angle greater than the critical angle and undergoes total internal reflection. After series of such total internal reflection, it emerges out of the core. Thus the optical fiber works as a waveguide. Care must be taken to avoid very sharp bends in the fiber because at sharp bends, the light ray fails to undergo total internal reflection.



FIBER AS A WAVEGUIDE

Principle/Mechanism of propagation:

In an optical fibre, the communication takes place by passage of light signals in the central core region through total internal reflection. Total internal reflection takes place only when a light ray travels from denser to rarer medium or from a region of higher refractive index to a region of low refractive index. When the angle of incidence at the core-cladding interface is greater than a certain critical angle, TIR takes place. We know that when the angle of incidence is exactly equal to critical angle, the refracted ray neither enters the rarer nor the denser medium instead grazes along the surface of the fibre.



Then by Snell's law, $n_1 \sin\theta_c = n_2 \sin 90^0$

Where , n_1 – refractive index of core

n_2 – refractive index of cladding

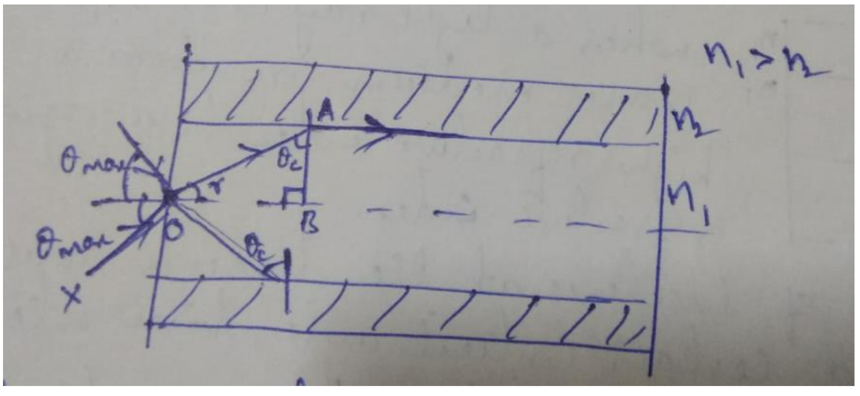
θ_c – critical angle

When the ray enters the fibre along the axis it just passes along the axis without any reflection (i=0). As the angle of incidence is increased, the angle of incidence at the core-cladding interface keeps decreasing. At a particular angle of incidence at the entry point is maximum (θ_{max}), the corresponding angle of incidence at the core-cladding interface will be equal to θ_c which means which means θ_{max} is the maximum angle of incidence at the entry point for which total internal reflection is possible. This angle is called angle of acceptance. The light cone with its vertical angle equal to twice θ_{max} is called cone of acceptance.

Numerical Aperture (NA):

It is a parameter which determines the signal carrying capacity of a given fibre.

Expression for Numerical aperture



Let us consider an optic fibre with refractive index of the core n_1 and RI of cladding n_2 ($n_1 > n_2$) placed in a medium of RI n_0. Let XO be a light ray entering the fibre at point O with an angle of incidence i_{max} such that after refraction it strikes the core-cladding interface at A with an angle of incidence equal to θ_c. Then the ray after refraction at A will graze along the core-cladding interface.

Applying Snell's law at the entry point O

$n_o \sin \theta_{max} = n_1 \sin r$ (1)

where, $r = 90-\theta_c$

$n_o \sin \theta_{max} = n_1 \sin(90-\theta_c)$

$n_o \sin \theta_{max} = n_1 \cos\theta_c$ (2)

Applying Snell's law at the core-cladding interface

$n_1 \sin\theta_c = n_2 \sin 90$

$n_1 \sin\theta_c = n_2$

$\sin\theta_c = n_2 / n_1$ (3)

Substituting equation 3 in equation 2, we get

$$n_0 \sin\theta_{max} = n_1\sqrt{1-\cos^2_{\theta c}}$$

$$n_0 \sin\theta_{max} = n_1\sqrt{1-\frac{n_2^2}{n_1^2}}$$

$$n_0 \sin\theta_{max} = n_1\frac{\sqrt{n_1^2-n_2^2}}{n_1}$$

$$\boxed{\sin\theta_{max} = \frac{\sqrt{n_1^2-n_2^2}}{n_0} = NA}$$

If the fibre is placed in air, the value of n0 will be 1, then $\sin\theta_{max} = \sqrt{n_1^2 - n_2^2}$. This value of sine of angle of acceptance is called the numerical aperture.

$\theta_i < \theta_{max}$

$\sin \theta_i < \sin \theta_{max}$

$\sin \theta_i < NA$ is the condition for propagation.

Experimental observations reveal that numerical apertures for the fibres used in short distance communication are in the range of 0.4 to 0.5, whereas for long distance communications numerical apertures are in the range of 0.1 to 0.3. it has been observed that smaller NA is not an advantage because it makes it harder to launch optical power into the fibre. Numerical aperture is also called the figure of merit of the optical fibres.

Fractional Index Change:

"It is the ratio of the refractive index difference between the core and claddingto the refractive index of the core of an optical fiber".

$$\Delta = \frac{n_1 - n_2}{n_1}$$

Relation between N.A and Δ:

Consider $\Delta = \frac{n_1 - n_2}{n_1}$

We have, $\Delta n_1 = n_1 - n_2$

WKT, $NA = \sqrt{n_1^2 - n_2^2}$ for air medium

$NA = \sqrt{(n_1 + n_2)(n_1 - n_2)}$

If $n_1 \sim n_2$, then

$NA = \sqrt{2 n_1 \Delta n_1}$

$NA = \sqrt{2\Delta}\, n_1$

Increase in the value of Δ increases N.A. It enhances the light gathering capacity of the fiber. Δ value cannot be increased verymuch because it leads to intermodal dispersion intern signal distortion.

Modes of propagation:

In an optic fibre, the light pulse that propagates in the core can behave both like wave and particle. When these pulses super impose leads to interference. Interference means both constructive and destructive interference. When the light pulses undergo destructive interference, its intensity fade out where as when the pulses interfere constructively the intensity increases. The wave mode that supports constructive interference is called modes of propagation and is determined by a parameter called V-number.

V-number: It is a parameter that determines the modes of propagation in a given fibre.

If the surrounding medium is air, then

$$V = \frac{\pi d}{\lambda} NA$$

Where ‘d’ is the core diameter, n1 and n2 are refractive indices of core and cladding respectively, ‘λ’ is the wavelength of light propagating in the fiber.

If the fiber is surrounded by a medium of refractive index n_0, then,

$$V = \frac{\pi d}{\lambda} \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

The maximum number of modes supported by the fiber is given by,

$$N = \frac{V^2}{2}$$

Cut –off wavelength (λ_c):

- V<2.407, the fibre can support only one mode and is classified as single mode fibre.
- V>2.407, the fibre can support only many modes and is classified as multimode fibre.

The wavelength corresponding to the value of V=2.407 is known as the cut-off wavelength (λ_c) of the fibre. At this particular wavelength, the multimode fibre switches over to single mode fibre.

Cut-off wavelength can be estimated using the equation,

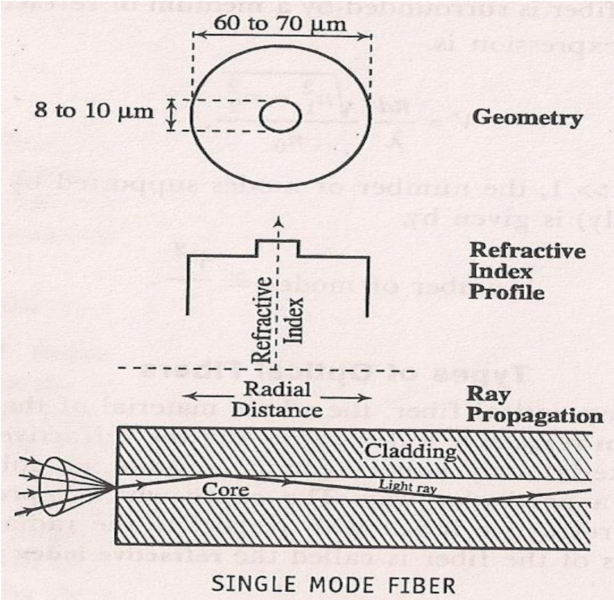
$$\boldsymbol{\lambda_c = \frac{\lambda V}{2.407}}$$

Types of optical fibers:

In an optical fiber the refractive index of cladding is uniform and the refractiveindex of core may be uniform or may vary in a particular way such that the refractive index decreases from the axis, radically. Depending on the refractive index profile and modes of propagation, optic fibres are classified into 3 types:

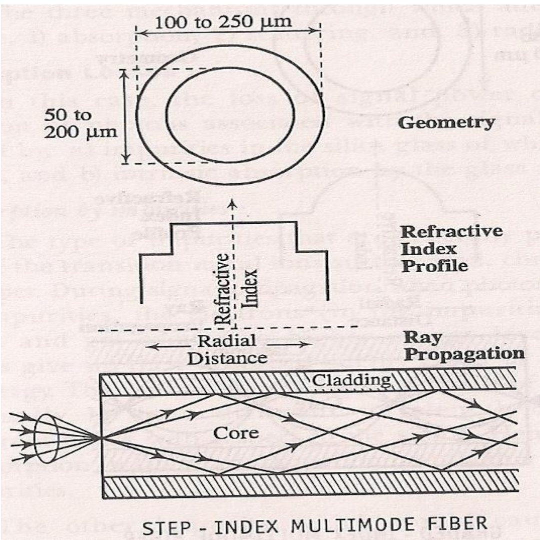
1. Single mode step index fiber
2. Multimode Step index multimode fiber
3. Graded index multimode fiber

1. **Single mode step index optic fiber:** Refractive index of core and cladding has uniform value;there is an increase in refractive index from cladding to core and $n_1>n_2$. The refractive index profile in this looks like a step function. The diameter of the core is about 8 to 10 μm and cladding diameter is of 60 to 70 μm. The core of the optic fibre is very narrow which can allow only one wave mode to pass through the fiber and hence, the name single mode step index fibre. Since the core allows one wave mode to pass through, the signals have to be fed sequentially. Therefore, speed of communication will be less. These fibres are not suitable for long distance communication. They can be used only in local area network (LAN) system.



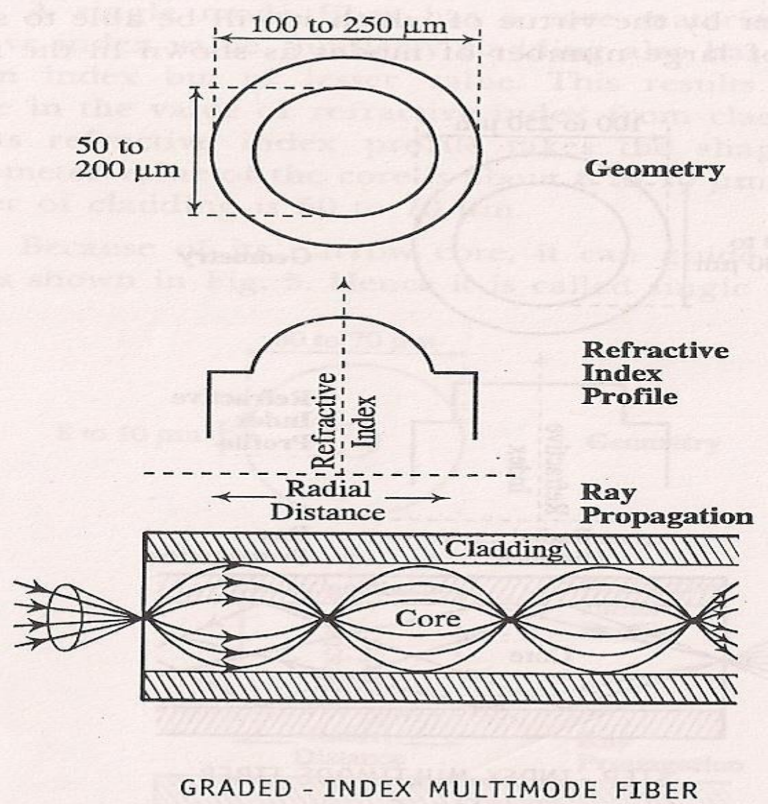
2. Multimode Step index optic fiber:

The refractive index core and cladding is uniform such that $n_1 > n_2$. It is similar to single mode fiber but core has larger diameter. The refractive index profile in this fibre also found to be a step function. The diameter of the core is about 50 to 200 µm and cladding diameter is of 100 to 250 µm. Since core has a larger diameter it can allow many modes to propagate as shown in figure. In these fibres many signals can be fed simultaneously. The pulse which enters the fibre with an angle of incidence i=0 will have shortest path length as it move along the axis of the fibre. As the angle of incidence increases, the number of reflections in the core region will also increase for a definite distance. The pulse which enters with the smallest angle of incidence will have shortest path length and the one which enters with the larger angle of incidence will have the longest path length. The speed of communication will be the same. So, the signals with shortest path length reach the end point early than the longest path length signals which leads to signal distortion. These fibres are useful for long distance communication and the main disadvantage is that signal distortion.Laser or LED is used as a source of light.



3. **Graded index multimode fiber:** It is also called GRIN. The refractive index of core is not a constant which decreases from the axis towards the core cladding interface. The refractive index profile shows semi circle which is shown in figure. The diameter of the core is about 50 to 200 µm and cladding diameter is of 100 to 250 µm. The pulse which enters the fibre with an angle of incidence i=0 will have shortest path length and the ray just passes along the axis of the fibre.

   The signal which enters along the axis will come out without any reflection. Whereas the signal with angle of incidence greater than zero will undergo refraction at every layer of the core and it bends when it moves from one layer to another layer. The path will be curvilinear which is as shown in the figure. When the signal moves through a region of higher RI its speed will be low and when it enters the region of lower RI its speed increases. By this mechanism the average speed of the signal with longest path length will be greater than the average speed of signal with shortest path length. Hence, the pulse distortion can be minimized. These fibres are useful for long distance communication. Laser or LEDis used as a source of light.



GRADED - INDEX MULTIMODE FIBER

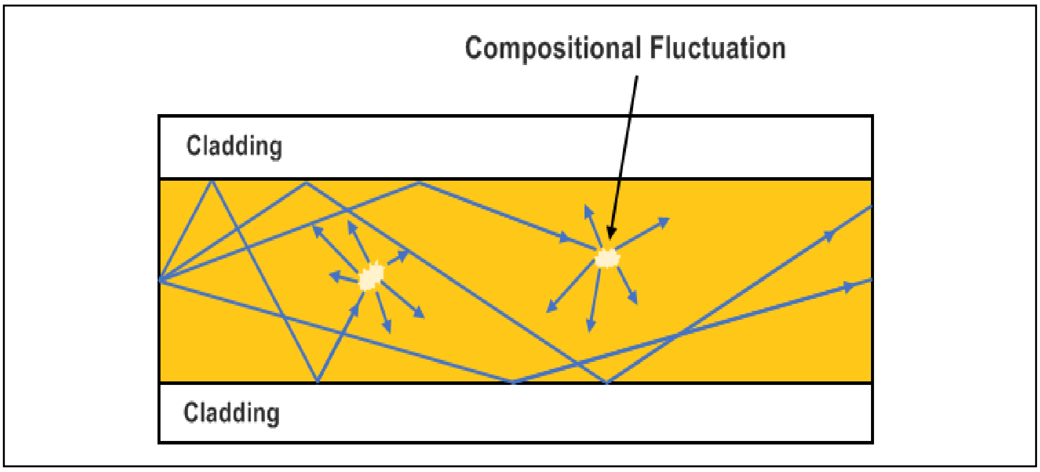
Attenuation:

Even though optic fibres are more advantageous than co-axial cu cable, loss of intensity is bound to happen. Attenuation is the loss of optical power as light travels through a fiber. It is expressed in decibel/kilometer [db/km]. A fiber with lower attenuation will allow more power to reach its receiver than a fiber with higher attenuation. Various factors are responsible for attenuation in an optical fibre namely

1. Absorption effects
2. Scattering effects
3. Radiation effects

Absorption effects:- when the light signlas pass through the core region absorption of the photons are likely to happen because glass is essentially made of SiO_2 which has a definite absorption band in the EM spectrum. Another impurity is the presence of impurities in the form of such as iron, chromium, cobalt and copper in the silica glass of which the fiber is made of. During signal processing photons interact with electrons of impurity atoms. The atoms are excited and de-excite by emitting photons of different characteristics. Hence it is a loss of energy. The other impurity such ashydroxyl ions (OH) causes significant absorption loss. The absorption of photons by fiber material itself is called intrinsic absorption.

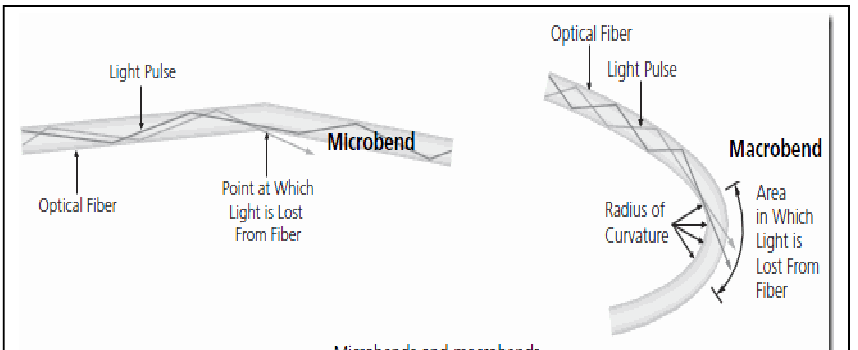
Scattering effects: ideally speaking along the core RI has to be constant. But in reality it is not easy to attain. Refractive index gradients will always be there. When the wavelength of the photon is comparable to the size of the particle then the scattering takes place. Because of the non uniformity in manufacturing, the refractive index changes with length leads to a scattering. This type of scattering is called as Rayleigh scattering. It is inversely proportional to the fourth power of wavelength. Scattering of photons also takes place due to trapped gas bubbles which are not dissolved at the time of manufacturing.



Radiation losses: Radiation losses occur due to macroscopic bends and microscopic bends. It is impossible to lay the optic fibres straight an always there will be a bending of fibres. The curvature of the fibre cannot be avoided.

Macroscopic bending: All optical fibers are having critical radius of curvature provided by the manufacturer. If the fiber is bent below that specification of radius of curvature, the light ray incident on the core cladding interface will not satisfy the condition of TIR. This causes loss of optical power.

Microscopic bending: Optical power loss in optical fibers is due to non- uniformity of the optical fibers when they are laid. Non uniformity is due to manufacturing defects and also lateral pressure built up on the fiber. The defect due to non uniformity (microbendings) can be overcome by introducingoptical fiber inside a good strengthen polyurethane jacket.



Microbends and macrobends

The net result of all these factors is determined by a parameter known as attenuation coefficient ‘α’ of the fiber, in units of db/km is given by

$\alpha = -\frac{10}{L}\frac{P_{out}}{P_{in}}$ dB/Km