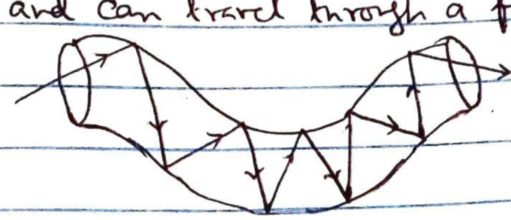
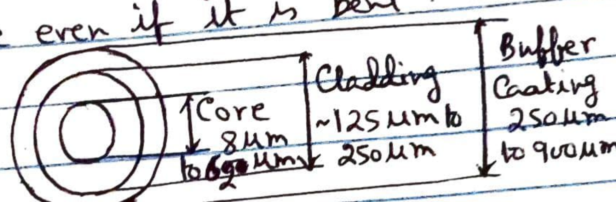
Fibre optics is a technology in which information in the form of electrical signal is converted into optical signal & then is transmitted from one place to other through optical fibre (OF) and then ~~reconverted~~ reconverted into electrical signal.

Definition: An OF is a cylindrical wave guide made of transparent dielectric, which confines and guides light waves along its length by total internal reflection (TIR)

Principle: When light enters one end of the fibre, it undergoes successive total internal reflections from sidewalls and travels down the length of the fibre along a zigzag path. Only a very very small fraction is escaped through sidewalls, emergent beam remains almost intact and can travel through a fibre even if it is bent.





Structure: An OF has 3 coaxial cylindrical regions.

i) The innermost light guiding region is core with diameter 8μm to 62.5μm

ii) The middle layer, surrounding the core is cladding with diameter 125–250μm. The refractive index (n_2) of cladding is always less than that of core (n_1) hence ensures total internal reflection at the core cladding interface, if light entering the core, strikes the core cladding interface at an angle greater than the ~~an~~ critical angle of reflection. Then all subsequent reflections will also be automatically TIR because of cylindrical symmetry.

iii) The outermost protective layer is called sheath or buffer coating, the diameter of which varies from 250μm to 900μm. The elastic buffer prevents abrasion and protects against physical damage & environmental effects.

Material: OF is prepared with glass or plastic, transparent to optical frequencies

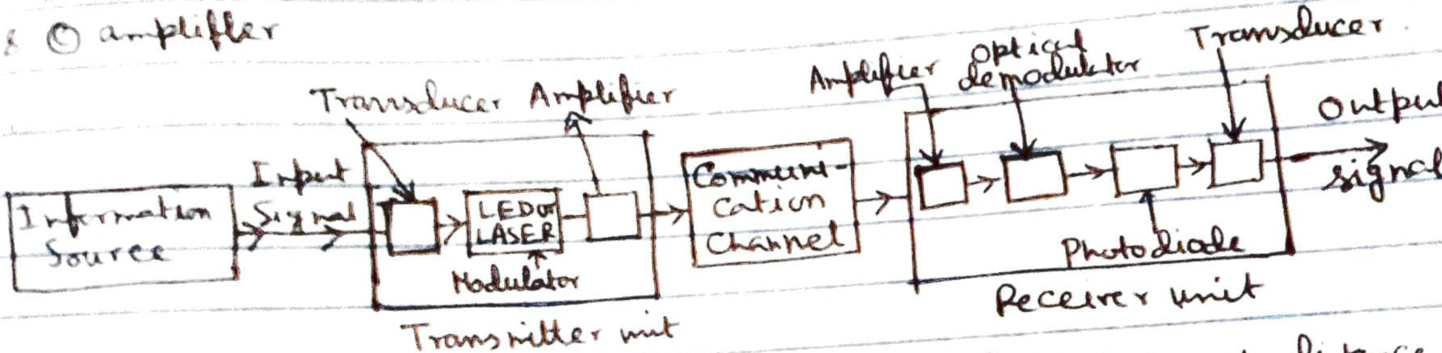
ⓐ All glass fibre: glass core cladded with a glass with less R.I. Main material is silica (SiO_2). It is either SiO_2 core & doped SiO_2 ($B_2O_3 \cdot SiO_2$) cladding or doped silica ($GeO_2 \cdot SiO_2$) core & pure SiO_2 cladding. Very low loss

ⓑ All plastic fibre: Perspex or polystyrene core and fluorocarbon or silicone resin cladding. Very high loss but large core diameter is possible

ⓒ Glass core cladded with plastic: Core is quartz, cladding is Teflon/silicone resin

OF Communication System: Any communication system transmits information from one place to another. It has 3 major components - Transmitter, Communication Channel & Receiver. The information signal can be anything like a video or audio clip (sound or light wave) or a variation in pressure or temperature with time. Above 3 components are required to transmit any such signal from one place to another.

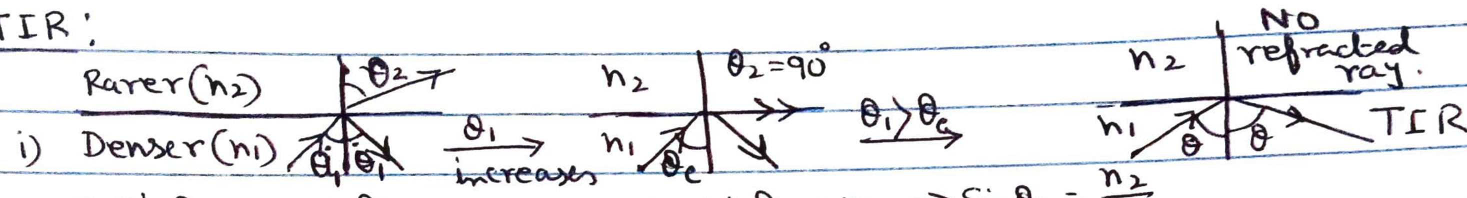
Transmitter: First, any non electrical information signal is converted into an electrical signal with the help of a suitable transducer. Then this electrical signal is mixed with a carrier wave & this is called modulation. After modulation the signal is amplified. Hence the transmitter unit consists of (a) transducer (b) modulator (information signal is coded in carrier wave) & (c) amplifier



Communication Channel: Depending on the nature of input signal, distance of transmission & security of signal, carrier wave is chosen & accordingly the communication channel is selected. Higher the frequency of carrier wave, more will be the amount of data that can be transferred in a given time & faster will be the speed. Hence em wave in visible/IR range will be better than radio or microwave as carrier wave. Atmosphere is the channel for radiowave while OF is the channel for visible/IR wave. For visible/IR wave LED/LASER diode is chosen as the source of carrier wave & the ~~input~~ electric signal from transducer is fed into the LED/LASER. The amplitude or frequency of the light emitted from LED/LASER is modulated by the input electric signal. The channel is responsible for the attenuation, loss, distortion and noise produced in the data & all these problems are mostly minimized in OF. To compensate the ~~loss~~ attenuation repeaters are used at specific intervals & the interval is larger for OF.

Receiver: This unit contains the amplifier which covers up the loss. Then the optical demodulator, which extracts the input signal from the carrier wave using interferrometric technique. This ~~of~~ light signal is then feed into a photodiode to convert it to an electrical signal. Finally again a transducer is used to change the electrical signal to the required form, if the input is not electrical one.

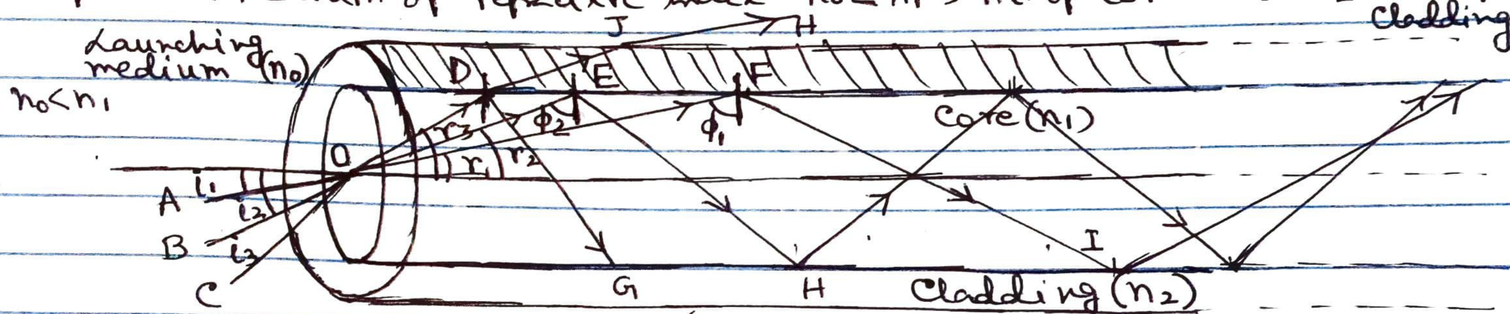
TIR:



$n_1 \sin\theta_1 = n_2 \sin\theta_2$ $\qquad$ $n_1 \sin\theta_c = n_2 \Rightarrow \sin\theta_c = \frac{n_2}{n_1}$

Using TIR light can be transmitted to a large distance by repeated TIR in a single medium without any loss to any other medium.

Launching and Propagation of light through OF : Let us consider an OF kept in a medium of refractive index $n_0 < n_1 \rightarrow$ r.i. of core & $n_0 < n_2 \rightarrow$ r.i. of cladding



The end of OF at which the light enters is the launching end. Let us consider three rays AO, BO & CO entering the launching end of OF at angle of incidence i_1, i_2 & i_3, $i_3 > i_2 > i_1$. After entering the core, light is bent towards the normal and refracted at angles r_1, r_2, r_3 respectively. These rays then strike the core-cladding interface at the points F, E & D at incidence angle ϕ_1, ϕ_2 & ϕ_3, $\phi_3 < \phi_2 < \phi_1$ ∴ $r_1 < r_2 < r_3$. Let us assume ϕ_2 is just greater than ϕ_c, the critical angle between core & cladding. ∵ $\phi_3 < \phi_2 \simeq \phi_c$, hence DG is partly reflected & other part will go inside cladding, DJ & then finally comes out from OF as JH. ∵ $\phi_1 > \phi_2 \simeq \phi_c$ hence the rays EH & FI will suffer TIR. Let us consider the angle $r_2 = \theta_c$, which is the maximum angle of refraction in the core medium at the point O, for which light will suffer TIR at the core-cladding interface, this angle θ_c is called the critical angle of propagation for the given OF. Any angle of refraction r in the core medium, at the launching point, such that $r > \theta_c$, will not result in TIR at the core-cladding interface. Corresponding angle of incidence at the launching ~~medium~~ end, $i_2 = i_{max}$ is the maximum angle of incidence at the launching end of OF, for which light inside the core will suffer only TIR at the core-cladding interface, repeatedly

Any ray incident at launching end with angle > i_{max} (ex i_3) will not be guided inside OF by TIR only. The angle i_{max} is called the ~~critical~~ angle of acceptance for the given OF (given n_1 & n_2) & given launching medium (given n_0), the maximum angle of incidence at the launching end of the OF w.r.t. the axis of the fibre, for which light will be guided along the fibre with TIR only. Because of the cylindrical symmetry of the core, if the first reflection at the core-cladding interface is TIR, all subsequent reflections will be TIR only. Larger value of i_{max}, accepts more light & is easier to launch light in OF.

Cone of acceptance: The cone with semi vertical angle as the angle of acceptance i_{max} or a full angle $2i_{max}$ is called the cone of acceptance, which contains light that is accepted & transmitted along the core of the OF with TIR at core cladding interface. Light incident at the launching end with angle of incidence > i_{max} will not remain 100% within the core & hence is not accepted/allowed in the core.

Expression for θ_c & i_{max}: At point O, $n_0 \sin i_{max} = n_1 \sin \theta_c$ — ①

At point E, $n_1 \sin \phi_c = n_2 \Rightarrow \sin \phi_c = \frac{n_2}{n_1}$. $\theta_c + \phi_c = 90°$.

$\therefore$ ~~$\sin\phi$~~ $\sin\theta_c = \sin(90° - \phi_c) = \cos\phi_c$. $\boxed{\cos\phi_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1}}$

① $\rightarrow$ $n_0 \sin i_{max} = n_1 \sin\theta_c = n_1 \cos\phi_c = \sqrt{n_1^2 - n_2^2}$

$\therefore \sin i_{max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$. $i_{max} = \sin^{-1}\left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right)$, $\theta_c = \sin^{-1}\left(\frac{\sqrt{n_1^2 - n_2^2}}{n_1}\right)$

Fractional refractive index change Δ: It is the fractional difference between the refractive indices of the core & cladding.

$\Delta = \frac{n_1 - n_2}{n_1}$, $\because n_1 > n_2$ & $(n_1 - n_2)$ is very small, so Δ is +ve & $\lesssim .01$.

Numerical Apperture NA: It is defined as the light gathering capacity of a given OF & is the characteristic of the OF only. It is defined as $NA = n_0 \sin i_{max} = \sqrt{n_1^2 - n_2^2}$, ~~for air~~ whatever be the launching medium. Typical value of NA lies in 0.1 to 0.5. ~~0.1 to 0.2 for~~

Relation between NA & Δ:

$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(n_1 - n_2)(n_1 + n_2)}$ $\because n_1 \sim n_2 \therefore n_1 + n_2 \simeq 2n_1$

$= \sqrt{(n_1 - n_2)2n_1} = \sqrt{2n_1^2 \frac{n_1 - n_2}{n_1}} = n_1\sqrt{2\Delta}$ $\left[\sin i_{max} = \frac{n_1}{n_0}\sqrt{2\Delta}\right.$

NA depends only on the material of OF, not on physical dimension of OF

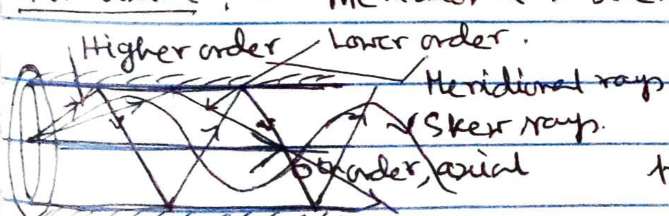
Modes of propagation: A plane em wave when travels in free space, it is a transverse em wave (TEM). When the light ray is guided through an OF, not all the rays launched at input end ~~can~~ are obtained at the output end. The light rays following zigzag path inside the OF suffer phase change. Hence light rays following some path will be in phase & undergo constructive interference while others suffer destructive interference & hence are lost. The light ray paths along which the waves are in phase inside the OF are allowed paths & are known as modes & they are finite in number. Each of these allowed paths correspond to a particular pattern of electric & magnetic field distribution such as transverse electric (TE), transverse magnetic (TM) & hybrid modes, combination of TE & TM. Each mode carries a portion of the light launched at the input end.

Types of modes: The axial ray travelling along the axis of the OF is 0^{th} order mode. The mode propagating with $\phi = \phi_c$ is the highest order mode. As ϕ is increased from ϕ_c the order of the mode decreases. The higher order modes suffer more reflections at the core cladding interface & travels longer path inside the OF than lower order modes. Hence, for lower order modes the fields & energy are more concentrated near the axis of the OF while for higher order modes, energy is distributed more towards the core cladding interface & hence there is more chance of leakage.

Number of modes: Number of modes that a fibre will support increases as Δ is increased i.e. as n_1 is increased or n_2 is decreased. Number of modes depends on the physical dimension of the OF. As core diameter, d, increases, the number of modes increases. It is inversely proportional to the wavelength of light λ.

Types of rays: Axial (going along axis of OF or $\parallel^{l}$ to it) & Non-axial.

Non-axial: — Meridional & Skew rays. Meridional rays passes through the axis of the OF & follow zigzag path. Skew rays do not cross the axis of OF, are helical about the axis.

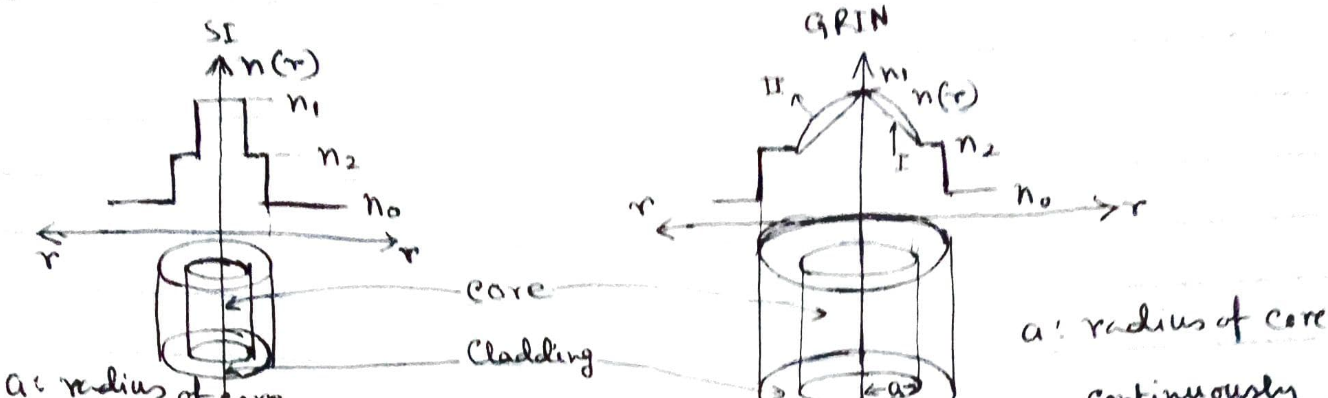


Classification of OF : ① Based on R.I. profile : Step index (SI) & Graded index (GRIN)

② Based on number of modes : Single mode & Multimode (SM) & (MM)

① Step index & Graded index fibre.

Variation of RI with r, distance from axis of OF, for SI & GRIN fibre



a: radius of core

a: radius of core

RI remains constant in the entire core region & there is a step down of RI value at the core cladding interface

$n(r) = n_1 (r<a)$, $n(r) = n_2 (r>a)$.

RI changes continuously in the core region as a function of r, from a maximum of n_1 value at the axis of OF, to the value n_2, at the core cladding interface. RI remains const (n_2) in cladding

GRIN : The variation of n(r) in the core can be of different type. linear (I), parabolic (II) or of some other type. The functional form of

$$n(r) = n_1\sqrt{1-[2\Delta(\tfrac{r}{a})^\alpha} \quad [r<a] \quad , \quad n(r) = n_2 \quad [r>a]$$

α is the grading profile index, $\alpha=1$ for linear, $\alpha=2$ for parabolic, $\alpha=0$ for step function

$n(r) = n_1$ when $r=0$, $n(r) = n_2$ when $r=a$.

② Single mode & Multimode fibre:

Single mode fibre : Very small core diameter & can support only one mode of propagation, the 0^{th} order mode.

Multimode fibre : Larger core diameter to support a number of modes.

Hence overall there can be three different type of fibres.

① Step index single mode (SISM)

② Step index multi mode (SIMM)

③ Graded index multimode (GIMM)

It is not possible to manufacture graded index single mode fibre.

Relation bet^n NA & Δ for a GRIN fibre :

For a SI fibre, $NA = n_1\sqrt{2\Delta}$

For a GRIN fibre $NA = \sqrt{n_1^2 - n_2^2} = \sqrt{n_1^2\left[1-2\Delta\left(\frac{r}{a}\right)^\alpha\right] - n_2^2}$

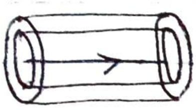
$$= \sqrt{(n_1^2 - n_2^2) - n_1^2 2\Delta\left(\frac{r}{a}\right)^\alpha}$$

$$= \sqrt{(n_1+n_2)(n_1-n_2) - n_1^2 2\Delta\left(\frac{r}{a}\right)^\alpha} = \sqrt{2n_1^2\Delta - n_1^2 2\Delta\left(\frac{r}{a}\right)^\alpha}$$

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

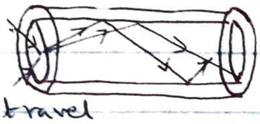
Comparison of propagation of light through SISM, SIMM & GIMM.

Step index single mode fibre : Core diameter 8-12 μm, Cladding dia ~125μm

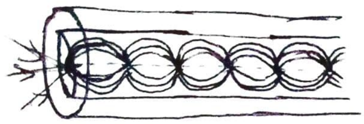


Light travels along a single path i.e along the axis, only the zero order mode is supported. Both Δ & NA are very small. Attenuation is minimum, faster transfer of data, no dispersion/noise so no change in the input signal for long distance. Suitable for long distance secured data transfer. As NA & hence acceptance angle is very small so launching light inside core is difficult. LASER diode is essential for launching light. The bandwidth it supports is > 3GHz - km.

Step index Multi mode fibre) Core diameter ~50 μm to 200 μm. Cladding diameter is 125 μm to 250 μm. Light travels along many zigzag paths of propagation inside the core & suffers different



number of TIR along the path. A finite number of modes are allowed. The rays entering close to the axis, the lower order modes travel close to the axis, suffers less number of TIR & travels less path length compared to the rays entering with higher angle of incidence close to i_{max}, the higher order modes. Hence lower order modes reach the output end earlier than higher order modes. Hence a dispersion of light is created at the output end and this is called inter modal dispersion. Both Δ & NA are large (<0.5) wrt. other 2 type of fibres. Attenuation of ~~data~~ signal is also large. Hence this type of fibre is not suitable for data transfer for a distance. Merit is launching of signal is easier & coupling is also easier for the same reason. Hence this kind of fibre is mainly used for data link or very short distance communication. The bandwidth it supports is less than ~~200~~ 50 MHz-km



Path of light inside a GRIN fibre.

Graded index **Multimode fibre**: The core can be considered as consisting of concentric layers of different refractive indices. The layers are so thin that refractive index variation can be considered as continuous inside the core. The diameters of core & cladding are 50-100μm & 125-150 μm.

Horizontal lines represent different layers of different R.I. $n_1 > n' > n'' > n''' > n_2$, n_1 at the axis & n_2 at the core-cladding interface.

As light enters the core at the input end, it strikes successive layers of lesser RI, hence through different layers light will be refracted more & more away from the normal & will strike ~~the~~ a layer with angle greater than the critical angle between that & next layers. Hence light will not further go towards cladding but reverted back towards the axis. Now it will traverse from lower to higher RI layers & hence light will be refracted towards the normal till it strikes the axis. After that again it will start moving away from the normal to successive layers, & ~~at~~ from certain layer, satisfying the condition for TIR, will be reverted back towards the axis. Thus for any mode of propagation, light will not follow a straight zigzag path rather it will follow a sinusoidal curve. Higher order modes will suffer TIR from layer closer to the cladding. Although higher order modes will travel more distance wrt a lower order one, but it will travel through a region with lesser RI & hence the speed will be more. Consequently all rays travelling through the fibre, irrespective of their modes, will have almost the same optical path length & ~~same time period~~ Hence reach the output end of the fibre at the same time. The intermodal dispersion present in a SIMM fibre is avoided in GIMM fibre because of the periodic focussing of the light inside the core of the fibre. Values of Δ & NA are in between those of SISM & SIMM fibre. Attenuation is also moderate. Though intermodal dispersion is not present but material dispersion exists. Though launching of signal is easier & medium distance travel is also effective but because of high cost can't be used for very long distance communication. Useful for LAN connection. Bandwidth varies from 200 MHz-km to 600 MHz-km

V-Number & Maximum number of allowed modes (N_m):

Number of allowed modes in a fibre, depends on the NA & also on the physical dimension of the fibre ie. core diameter & the wavelength of light. Once NA is fixed ie. materials for core & cladding are fixed, the light gathering capacity at the input end is fixed. But how exactly that light will be transmitted through the OF, will depend on radius of core (a) & wavelength of light (λ) inside the core. Apart from the frequency (wavelength) of light; as exact paths also depend on the core radius hence we can define a frequency of light inside the core, that is normalized w.r.t. the physical dimension of the core. we call it a normalized frequency or V number. The structure of OF is such that as the core radius is increased, keeping every other factors constant, the light travels with more & more modes. V-number is given by

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \quad \text{--- (1)}$$

As a is increased number of allowed modes increases but for each added mode there exist a definite value of V below which the mode is cutoff or is not added.

For $V = 0$ to < 2.405, a single mode is allowed inside the fibre
for $V = 2.405$ to < 3.83, two modes are allowed inside the fibre.
for $V = 3.83$ to < 4, three modes are allowed inside the fibre.

For $V > 10$, the max. number of allowed modes in a SI fibre is given by $N_m = \frac{V^2}{2}$ & for a GRIN fibre $N_m = \frac{V^2}{4}$.

Formula (1) suggests that number of modes inside a given OF depends on the wavelength of light λ, & by varying λ the number of modes inside a fibre can be changed.

For $\lambda_c \geq \frac{2\pi a}{2.405}\sqrt{n_1^2 - n_2^2}$ any fibre will operate in single mode transmission. Hence, for a given fibre, by increasing or decreasing the wavelength of incident light, number of modes inside a fibre can be decreased or increased.

Advantages of OF: (1) Long distance transmission (2) Very high bandwidth (~TeraHz) (3) Small size (dia ~ hair strand) & weight, (4) Electric isolation (dielectric coating so no chance of spark/short circuit), (5) Immunity to interference (EMI/RFI) or crosstalk or noise, (6) low transmission loss, (7) Signal security, (8) Ruggedness & flexibility, (9) Few repeaters & ease of maintenance, (10) Low cost (made of silica)