Optical components

Optical transmission : Data transfer through light

Unit 1

Speed of light in vacuum } 3×10^8 m/s

$\frac{k_B T}{q} = 0.025$ eV

$1 eV = 1.6 \times 10^{-19}$ J

Copper cable vs optical ~~cable~~ fiber → uses silica

* low transmission loss
* closed environment → immunity to interference
* small size, weight.
* silicon / Ge cannot be used for optical sources
  → indirect bandgap material
  → can be used for detectors.

~~clem~~ Elements of optical ~~source~~ fiber :

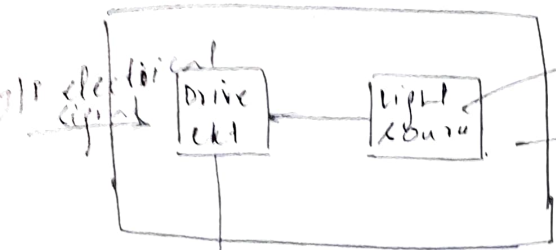
message source → Tx → Transmission channel → Rx → Dest

↓

OF made of glass + plastic

note :

Tx → electrical to light



→ generates, modulates

→ laser/led

→ ~~conversion~~ driving of electrical to light.

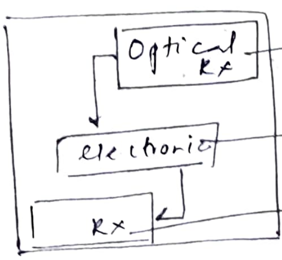
connector → temporary joining

splicing → permanent joining (fusion welding of core).

coupler/beam splitter → splits the signal

Regenerator $\xrightarrow{\text{aka}}$ amplifier (to boost)

↳ recieve, and convert electronically amplify and again convert to optical



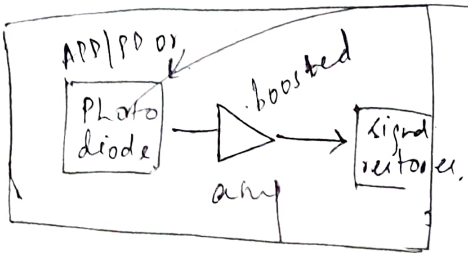
→ converts light → electrical

→ receives electrical signal + amplify

→ electrical signal → optical

<u>Rx</u> → convert light to electrical signal

→ detector (detect 0s & convert)



Telecommunication wavelength } λ used for Tx & Rx
- 1550 nm
↓
min attenuation
less loss window
(1300 nm - 1550 nm)
↳ low dispersion.

Spectral Bands (ITUT standard)

1260 - 1675 nm ⟶ min dispersion / loss.

↳ region split into 6 diff parts.

O - original band - 1260 - 1360 nm

E - Extended - 1360 - 1460 nm

S - short - 1460 - 1530 nm
(1550 nm lies here)

C - conventional - 1530 - 1565 nm
(EDFA)

L - long band - 1565 - 1625 nm

U/XL - ultra long - 1625 - 1675 nm.

O band ⟶ first special band used for tele commn.

✱ distortion min

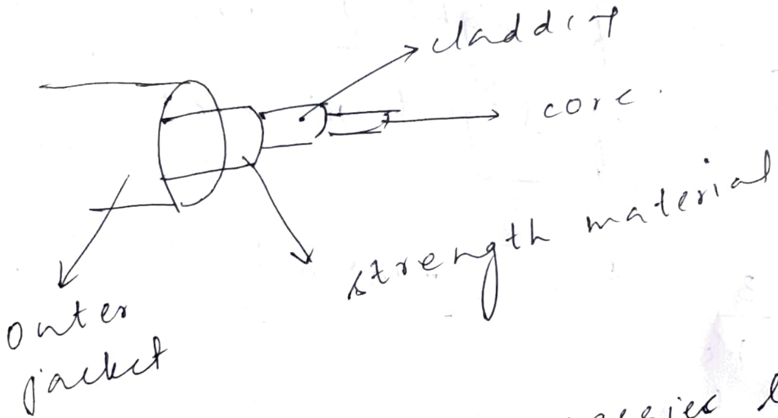
E-band → $\boxed{\text{least used}}$, attenuation; dispersion
↳ highest.

s band → used in PON

c band → $\boxed{\text{lowest loss}}$ window, used metro, submarine
(WDM + EDFA)

L band → $\boxed{\text{second lowest loss}}$ window, If c band is occupied then used

U / XL → network monitoring purpose

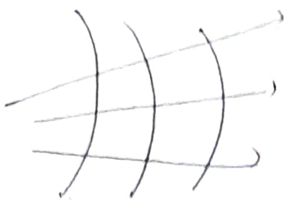


core → very thin, carries light from Tx to Rx
★ $\boxed{\text{higher refractive index}}$ ~~than cladding~~
(glass)

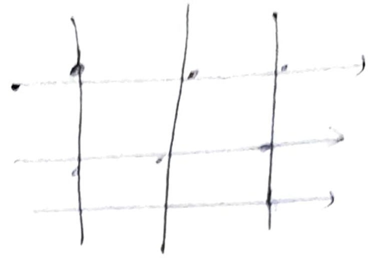
cladding → lower refractive index.
(plastic)

buffer → protection
(plastic)

Nature of light



wave nature
(spherical)
waveform



partical nature
(plane)
waveform

* speed depends on Refractive Index

$$\boxed{\eta = \frac{\text{speed of light in free space}}{\text{speed of light in material}}}$$

$\times$ speed $= \frac{3 \times 10^8}{1.5} = \underline{\underline{2 \times 10^8 \ m/s}}$ → speed in optical fibre

1.5 → RI of optical fiber

$$\boxed{\text{lower RI} = \text{Higher speed}}$$

speed of light in water $= \frac{3 \times 10^8}{1.33}$

1.33 → RI in water.

$$\boxed{RI \propto \frac{1}{\text{speed}}}$$

High RI

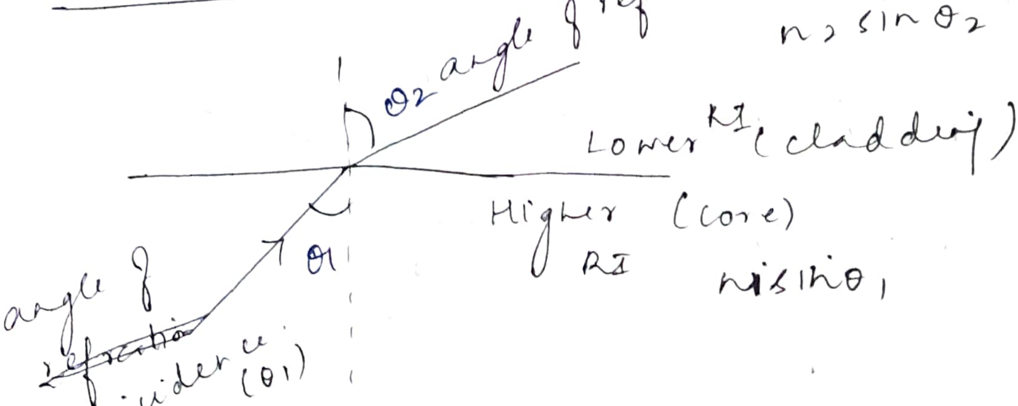
||||| → lower speed

Low RI

| | | | → Higher speed
(λ increases)

High to low → direction (angle) changes due to velocity change

Snell's Law



When angle of I ↑, ~~RI~~ reflection.

$\uparrow$ angle from higher RI to lower RI

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Sum

$\theta_1 = 38°$

$n_1 = 1.51$

$n_2 = 1.46$

$$1.51 \sin 38 = 1.46 \sin\theta_2$$

$$\sin\theta_2 = \left[\frac{1.51}{1.46}\right] \sin 38$$

$$= \underline{\underline{39.55°}}$$

CRITICAL ANGLE (θ_c)

* when $\theta_1 \uparrow$ at a point $\theta_2 = 90°$

$\Rightarrow$ light travels in the boundary of the two material (core-cladding boundary)

$\therefore$ this $\theta_1 \rightarrow$ critical angle.

$$\boxed{n_1 \sin\theta_1 = n_2 \sin 90°} \quad 1$$

* $\Rightarrow$ $\boxed{\theta = \sin^{-1} \frac{n_2}{n_1}}$

$\Rightarrow$ $\theta_i < \theta_c$ → refracted

∴ $\theta_1 = \theta_c$ → reflected back from boundary (mirror)

$\theta_1 > \theta_c$ → Total Internal Reflection

TIR ∴ condition

$\theta_1 > \theta_c$ → order to propogate light internally.

RI core > RI cladding ($n_1 > n_2$)

Types of fiber

optical fibers classification
- RI profile
- number of modes

RI profile → how RI is changing → 2 types
- step change → step profile
- gradual change → gradient profile (periodic change)

Modes
- single mode
- multimode

% Formulas

① Snells Law : $n_1 \sin\theta_1 = n_2 \sin\theta_2$ (RI, angles)

② critical angle : $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

③ numerical aperature : $nA = \sqrt{n_1^2 - n_2^2}$ (normally 0.1 - 0.4)

(light gathering capacity of optical fiber)

$nA \approx \cancel{n_1} \sqrt{2\Delta}$ → core / cladding Index difference

$\boxed{\Delta = \frac{n_1 - n_2}{2n_1}}$

④ Acceptance angle } $\theta_A = \sin^{-1}(NA)$

⑤ ~~Number of modes~~ V parameter $= \frac{2\pi\lambda}{\lambda(NA)}$ $\frac{2\pi a \times NA}{\lambda}$ → core radius

(normalized frequency) V parameter.
used to calculate no of modes, to determine single mode condition

⑥ → for SI

$M = V^2/2$ $V^2/4 \rightarrow GI$

↳ number of modes

$\boxed{\text{single mode : } V < 2.405}$ → cut off freq condn

$\boxed{\text{multimode : } V > 2.405}$

Sums

① $\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

$= \sin^{-1}\left(\frac{1}{1.48}\right) = \underline{\underline{42.5^\circ}}$

② $n_1 = 1$ → air
$n_2 = 1.52$ → glass

$\phi_1 = 30° \theta$

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$1 \sin 30^\circ = 1.52 \sin\theta_2$

$\frac{1}{2} = 1.52 \sin\theta_2$

$\sin\theta_2 = \frac{1}{2} \times 0.329$

$\theta_2 = \sin^{-1}(0.329) = \underline{\underline{19.2^\circ}}$

3) $n_1 = 1.48$ $\quad 1.48 > 1.46.$

$n_2 = 1.460$

a) $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

$\theta_c = \sin^{-1}\left(\frac{1.46}{1.48}\right) = 80.58°$

b) $NA = \sqrt{n_1^2 - n_2^2} = 0.242$ (normally 0.1–0.4)

$= \sqrt{(1.48)^2 - (1.46)^2}$

c) $\theta_A = \sin^{-1}(0.242) = \underline{\underline{14.03°}}$

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4) $\Delta = 2.0\% = \frac{2}{100} = 0.02$

$n_1 = 1.480$

~~$n_2 =$~~

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

$= 1.480\sqrt{2(0.02)} = \underline{\underline{0.296}}$

b) $\theta_A = \sin^{-1}(NA) = \sin^{-1}(0.296)$

$= \underline{\underline{17.22°}}.$

c) $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

$n_2 = n_1(1-\Delta) = 1.48(1-0.02)$

$= \underline{\underline{1.450}}$

$\theta_c = \sin^{-1}(n_2/n_1) = \sin^{-1}\left(\frac{1.45}{1.48}\right)$

$= 1.369$ rad

$= \frac{1.369}{0.174533}$

$= 7.85^\circ$

---

(5) $V = 26.6$

$\lambda = 1300 \times 10^{-9}$ m

$a = 25 \times 10^{-6}$ m

core radius

$$\boxed{V = \frac{2\pi a}{\lambda} \times NA}$$

$$NA = V \times \frac{\lambda}{2\pi a}$$

$$= \frac{26.6 \times 1300 \times 10^{-9}}{2 \times \pi \times 25 \times 10^{-6}}$$

$$= 0.22$$

---

(6) $n_1 = 1.48$

$n_2 = 1.476$

$a = 4.4 \times 10^{-6}$

$\lambda_c = 1250$ nm

$$V = \frac{2\pi a}{\lambda} \times NA$$

note

single mode a
4 - 6 μm
(radius)

$$Na = \sqrt{n_1^2 - n_2^2}$$

$\Rightarrow V = 1.39$

$\Rightarrow V < 2.405$

i.e single mode fiber.

---

(7) core dia $= 62.5$ μm $\Rightarrow a = \frac{62.5}{2} = 31.25$ μm

$\Delta = 1.5\% = 0.015$

$n_1 = 1.48$

$\lambda = 850$ nm

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

$$= 1.48 \sqrt{2(0.015)}$$

$$V = \frac{2\pi a}{\lambda} \times NA$$

$$= 59.2$$

$$M = \frac{V^2}{2} = \frac{(59.2)^2}{2} = 1753$$

Ans

8) $n_1 = 1.48$

$a = 25 \times 10^{-6}$

$\Delta = 0.01$

$\lambda = 860, 1310, 1550$

$$\boxed{V = \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta}}$$

sub for 3 diff λ

$$\boxed{M = \frac{V^2}{2}}$$

at 860 nm = V 38.2 $M = 729$

1310 nm = $V = 25.1$ $M = 315$

1550 nm $V = 21.2$ $M = 224$

---

9) $\frac{\text{Power cladding}}{P \text{ total}} = \frac{4}{3\sqrt{M}}$

↓ in the fiber

$$\boxed{P_{core} = P_t - P_{cladding}}$$

---

3 elements of OF

- source - led/Laser
- channel
- receiver → photo/pin diode

Skew ray ⟶ takes electrical path in OF

Mode ⟶ pattern in which the electromagnetic field is distributed.

Mode theory for circular waveguide

circular Modes in step Index fibre.

OF ⟶ circular waveguide with cylindrical coordinates.

Wave eqn for step Index fiber ✗ ✗ 10m (Refer PPT)

Assumption: Most of the light travels in the (i) core (due to asymmetric nature of the core) and some in (ii) cladding (outside core)

the results obtained (E, H) ⟶ 1

* Using the results obtained (E, H), by separation of variable method,

* $E_z = A F_1(r) F_2(\phi) F_3(z) F_4(t)$ ⟶ 2

$F_1(r)$ ⟶ radius of core

$F_2(\phi)$ ⟶ phase

$F_3(z)$ ⟶ prop direction

$F_4(t)$ ⟶ time

* The time and z dependent factors are given by (combining z and t)

$F_3(z) F_4(t) = e^{j(\omega t - \beta z)}$

* $F_2(\phi) = e^{j\nu\phi}$

ν ⟶ can be +ve / -ve.

Speciality Optical Fibers

↳ fabricated for peculiar applications

Types

↳ polarization maintaining fibers (PMF)

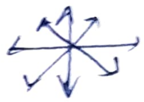
↳ Dispersion compensating fibers (DCF)

↳ Photonic crystal fibers (PCF)

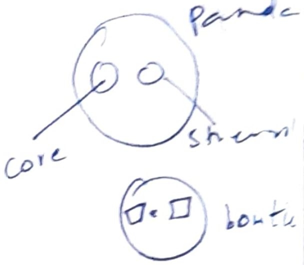
① PMF ✱ 4m — retains polarization state. lasers, high data bit rates

Polarization - orientation of light

unpolarized



polarized



* create artificial defect in OF to maintain polarization (during manufacturing)
  - ↳ panda
  - ↳ bow tie
  - ↳ eleptical clad

✱ ② DCF

↳ negative dispersion coeff fiber.

↳ ISI

Inter symbol interfrence

Input (2 pulses)

(output)

some component travels faster than other ∴ widening of pulses ⇒ collision / interfrence

* Unit of dispersion · ps/nm·km → length.

ps → pulse time

nm → pulse brodening.

Purpose : nullify the accumulated fiber dispersion

→ +ve overall dispersion.

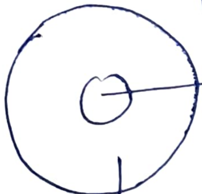
attenuation ↑ ∴ placed b/w preamp & booster amp of EDFA

-X-

③ Photonic crystal Fiber

conventional fibers

made of silica/glass..



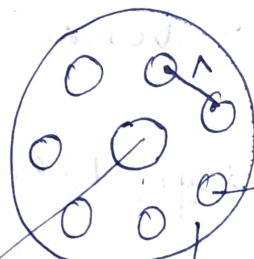
→ core $n_1 > n_2$

→ cladding

* light confined to core by TIR

Limitation : loss, non linear effects.

Photonic crystal fibers



→ air holes (RI = 1)

core

can act as cladding (silica)

core → solid

→ hollow (RI = 1) (Photonic Bandgap effect) → no propogation

→ modified TIR

→ RI for airhole region min, silica region max.

Parameters dependent for design

* pitch (Λ) → dist b/w one air hole to another

* d/Λ → air filling fraction ratio

* ↳ dia of airhole.

Attenuation

↳ causes

↳ fading / absorption

↳ scattering (Rayleigh, mies)

↳ bending of fiber — micro bending / macro

signal degradation in OF

* signal attenuation : determines max unamplified or replicated less distance b/w Tx and Rx.

* signal distortion → causes optical pulses to broaden resulting in overlapping of pulses.

↳ limits info carrying capacity of a fiber.

Basic attenuation mechanisms :

* absorption, scattering, radiative losses / bending loss

absorption → related to fiber material

scattering → related to material & structural imperfection

radiative losses / bending loss → originates from perturbation of fiber geometry.

Attenuation unit : $P(z) = P(0) e^{-\alpha_p z}$

$$\boxed{\alpha_p = \left(\frac{1}{z}\right) \ln\left[\frac{P(0)}{P(z)}\right]}$$

$P(0)$: optical power at $z = 0$.

α_p : fiber attenuation coeff

$\alpha\,(dB/km) = 4.343 \times \alpha_p\ (km^{-1})$

Absorption : 3 mechanisms

→ Impurities in fiber material.

→ Intrinsic absorption

→ Radiation defects.

* absorption by atomic defects :

eg → missing molecules, O_2

defects in structure → almost negligible

* Extrinsic absorption by impurity atom : results mainly from oxyhydrogen flame (OH).

* Intrinsic absorption : electronic absorption in UV region

EA $\quad \alpha_{UV} = C e^{E/E_0}$

IA $\quad \alpha_{IR} = 7.81 \times 10^{11} \times \exp\left(\frac{-43.43}{\lambda}\right)$

* Scattering Losses
  * due to microscopic variation in material density.
    - ↳ compositional fluctuation
    - ↳ defects during fiber manufacture.
  * Rayleigh scattering is inversely proportional to λ.
* Bending Loss : macroscopic or microscopic bends.

macro : tight bends induced in fiber itself.

micro : deformations and damage to core-cladding surface

Radius of curvature $\propto \frac{1}{\text{Bending loss}}$.

microbending loss > macro

* safe bend radius - 100 mm dia

* pressure sensor can be made using bending loss.

* ~~core~~-cladding loss

$\rightarrow$ For step-Index fiber:

loss for mode of order (ν, m)

$$\alpha_{\nu, m} = \alpha_1 \frac{P_{core}}{P} + \alpha_2 \frac{P_{clad}}{P}$$

* for low order modes,

$$\frac{P_{core}}{P} = 1 - \frac{P_{clad}}{P}$$

so total loss,

$$\alpha_{\nu m} = \alpha_1 + (\alpha_2 - \alpha_1) \frac{P_{clad}}{P}$$

* For graded Index fibers,

$$\alpha(r) = \alpha_1 + (\alpha_2 - \alpha_1) + \ldots$$

Signal distortion in fiber

* **Dispersion** : distorts both pulse and analog modulation signals
* no power is lost in dispersion, only shape changes
* **Pulses dispersion** : ps/nm/km.

Dispersion

- intermodal delay or modal delay
- intramodal or chromatic
  - → material
  - → waveguide
- polarization or mode.

Modal delay : only in multimode fiber

each mode having a diff value of group velocity at single frequency

⇒ no of modes & length of fiber

$$\Delta T = T_{max} - T_{min} = n_1/c\,(L \sin \phi_c - L)$$

$$= (L n_1^2 / c n_2)\,\Delta.$$

Fiber capacity : bit rate - dist product (BL)

$\Delta T < 1/B$: general requirement

$\Delta T \leq 0.1/B$: high performance link

* How to minimize effect of modal dispersion

$$V = \frac{2\pi a}{\lambda}(NA).$$

* By increasing λ, change NA
* reduce a
* Delay is less in graded index than step index.

Chromatic dispersion : material & waveguide

↳ only in single mode fibers

depends on λ.

Material dispersion : λ dependent, pulse spreading ∴ choose narrow spectral width source or ~~length~~ longer λ source

Eg: LASER

$$\sigma_g = L\sigma_\lambda \, |D_{mat}(\lambda)|$$

~~D_{mat}~~ $D_{mat}(\lambda)$: material dispersion

Waveguide dispersion : depends on fiber design

* fraction of light power propogating in cladding travels faster than light confined to core.

$$\sigma_{wg} = \frac{n_2 L \Delta \sigma_\lambda}{c\lambda} \; V \frac{d^2(Vb)}{dV^2}$$

* Polarization mode dispersion

* due to slightly different velocity for each polarization mode due to lack of perfect symmetricity.

$$\Delta \tau_{pol} = \left| \frac{L}{V_{gx}} - \frac{L}{V_{gy}} \right|$$

Rms value :

$$\langle \Delta \tau_{pol} \rangle = \sqrt{D_{pol} L}$$

Chromatic/total dispersion :

$$\sigma_{ch} = D_{ch}(\lambda) L \sigma_\lambda$$

Problems (attenuation)

(1) A low loss fiber has avg loss of 3db/km at 900nm. Compute the length over which

(a) power decreases by 50%

(b) power decreases by 75%.

Soln

$$\boxed{\alpha = 10 \times \frac{1}{z} \log\left(\frac{P(0)}{P(z)}\right)}$$

Given: $\alpha = 3 db/km$

$\frac{P(0)}{P(z)} = 50\% = 0.5$

$z = ?$

$3 db/km = \frac{10}{z} \log 0.5$

$z = \frac{10}{3} \log 0.5$

$= 3.3 \log 0.5$

$= 993 m \approx 1 km$

(b) $\cancel{z = \frac{10}{3} \log 0.75 = 412 m}$ remaining power.

$\frac{P(0)}{P(z)} = 100 - 75 = 25\%$

$\Rightarrow 0.25$

$= \frac{10}{3} \log 0.25$

$z = 1996 m \approx 2 km.$

(2) For a 30 km long fiber, attenuation is 0.8 dB/km at 1300 nm. If 200 μW power is launched at the I/P of the fiber, find power O/P.

<u>Given</u>

$\alpha = 0.8$ dB/km

$\lambda = 1300$ nm

$P(0) = 200 \times 10^{-6}$ W

$z = 30$ km

$P(z) = ?$

$$\alpha = 10 \times \frac{1}{z} \log\left[\frac{P(0)}{P(z)}\right]$$

$$\frac{0.8}{10} \times 30 = \log\left[\frac{\cancel{P(0)}\ 200 \times 10^{-6}}{P(z)}\right]$$

$$\Rightarrow 2.4 = \log\left[\frac{200 \times 10^{-6}}{P(z)}\right]$$

Taking antilog

$$10^{2.4} = \frac{200 \times 10^{-6}}{P(z)}$$

$$P(z) = \frac{200 \times 10^{-6}}{10^{2.4}}$$

$$= \frac{200}{251.2} \times 10^{-6}$$

$$P(z) = \underline{0.796\ \mu W}$$

(3) When a mean optical power launched into an 8 km length of fiber is 120 μW, then the mean optical power at the fiber o/p is 3 μW, find

(a) overall signal attenuation in dB

(b) overall signal attenuation for a 10 km optical link using the same fiber with the splice at 1 km interval, each splice giving an attenuation of 1 dB/km.

Soln Find for 8 km.

$\alpha = ?$

$z = 8\,km$

$P(0) = 120 \times 10^{-6}\ W$

$P(z) = 3 \times 10^{-6}\ W$

$$\alpha = 10 \times \frac{1}{z} \log\left[\frac{P(0)}{P(z)}\right]$$

$$= 10 \times \frac{1}{8} \log\left(\frac{\overset{40}{\cancel{120}}}{\cancel{3}}\right)$$

$$= 1.25 \log(40)$$

$$= 1.60 \times 1.25$$

$$= \underline{\underline{2}}$$

$\therefore$ For 1 km $\alpha = \frac{2}{8} = \frac{1}{4} = \underline{\underline{0.25}}$

(b) For 10 km $= 0.25 \times 10 = 2.5 +$ splice loss.

$2.5 + 9 = 11.5$ //

(4) A continuous 12 km long optical fiber link has a loss of 1.5 dB/km

(a) What is the minimum power level ~~required~~ that must be launched into the fiber to maintain as optical power level of 0.3 μW at the receiving end

(b) What is the required I/P power if the fiber has a loss of 2.5 dB/km?

Soln

$\alpha = 1.5$ dB/km

$z = 12$ km

$P(z) = 3 \times 10^{-6}$

$P(0) = ?$

$$\alpha = 10 \times \frac{1}{z} \log\left[\frac{P(0)}{P(z)}\right]$$

$$1.5 = \cancel{10\left(\frac{1}{3 \times 10}\right)} \; \frac{10}{12} \log\left(\frac{P(0)}{0.3 \times 10^{-6}}\right)$$

$$\frac{1.5 \times 12}{10} = \log \frac{P(0)}{0.3 \times 10^{-6}}$$

$$1.8 = \log \frac{[P(0)]}{0.3 \times 10^{-6}}$$

$$10^{1.8} = \frac{P(0)}{0.3 \times 10^{-6}}$$

$$P(0) = 10^{1.8} \times 0.3 \times 10^{-6}$$

$= 18.9 \mu W$

Problems

(ii) $\alpha = 2.5$ dB/km

$$2.5 = \frac{10}{2} \log \left(\frac{P(0)}{0.3\times10^{-6}} \right)$$

$$10^{3} = \frac{P(0)}{0.3\times10^{-6}}$$

$$P(0) = 300 \mu W.$$

---

(5) Optical power launched into the fiber at transmitter end is 150 μW. The power at the end of 10 km ~~fiber~~ length of the link working in first window is −38.2 dBm. Another system of the same length working in the second window is 47.5 μW. the same length system is working in the third window has 50% of launched power. Calculate fiber attenuation for each case and mention the wavelength of operation?

Ans

First window,

(i) $10 \log P(z) = -38.2$

$\log P(z) = -3.82$

$P(z) = 10^{-3.82}$

$P(z) = 151 \mu W$