Assignment - 3:

1. Signal gain is defined as,

$$G = \frac{P_{s,out}}{P_{s,in}} \quad \text{—— (1)}$$

where, $P_{s,out}$ & $P_{s,in}$ are the output & input powers.

The radiation intensity at photon energy $h\nu$ varies exponentially with distance travelled in lasing ~~cav~~ cavity. So, gain in SOA is given by:

$$G = \exp[\Gamma(g_m - \bar{\alpha})L] = \exp[g(z).L]. \quad \text{—— (2)}$$

where, Γ = optical confinement factor of the cavity.

g_m = material gain coefficient.

$\bar{\alpha}$ = effective absorption coefficient of material.

L = amplifier length.

$g(z)$ = overall gain per unit length

Equ(2), shows gain increases with device length. But, internally gain is limited by gain saturation.

This is due to the dependence of carrier density ~~at~~ in the gain region on optical input density. As the input signal is increased, excited carriers are depleted away from active region. When there is sufficiently large input ~~the~~ power, further increase in input power ~~no~~ longer yield an appreciable change in output level, since there are not enough excited carriers to provide an appropriate level of stimulated emission.

An expression for gain G as a function of input power can be derived by examining the gain parameter $g(z)$. This depends on - signal wavelength & carrier density.

$$g(z) = \frac{g_0}{1 + \frac{P_s(z)}{P_{amp,sat}}} \quad \text{—— (3)}$$

where, $P_s(z)$ → signal level at point z,

g_0 = unsaturated medium gain per unit length.

$P_{amp,sat}$ = amplifier saturation power [internal power at which gain per unit length is halved.

Gain decreases with increasing signal power.

$g(z)$ is gain per unit length, in an incremental length dz the light power increases by-

$$dP = g(z) P_s(z) dz. \quad — (4)$$

Substituting (3) in (4) & rearranging terms,

$$g_0(z) dz = \left[\frac{1}{P_s(z)} + \frac{1}{P_{amp,sat}} \right] dP.$$

Integrating,

$$\int_0^L g_0(z)\, dz = \int_{P_{s,in}}^{P_{s,out}} \left(\frac{1}{P_s(z)} + \frac{1}{P_{amp,sat}} \right) dp.$$

$$G = 1 + \frac{P_{amp,sat}}{P_{s,in}} \left[\frac{G_0}{G_1} \right]$$

$G_0 \rightarrow$ single pass gain in absense of light $= \exp(g_0 L)$.

This illustrates dependence of gain on input power also.

2. ~~External pumping mechanism:~~

External current injection is pumping method used in SOAs to create the population inversion needed for having gain mechanism.

Carrier density in exited state is governed by rate equation

~~that governs the carrier density~~

$$\frac{\partial n(t)}{\partial t} = R_p(t) - R_{st}(t) - \frac{n(t)}{\tau}. \quad — (1)$$

where, $R_p(t) = \frac{J(t)}{qd}$ is the external pumping rate from injection current density. $J(t)$ into an active layer of thickness d, τ_p is combined state time constant coming from spontaneous emission carrier-recombination mechanisms.

$$R_{st}(t) = \tau a v_g (n - n_{th}) N_{ph} = \Gamma v_g N_{ph} \quad — (2)$$

is net stimulated emission rate.

Γ = optical confinement factor.

a = gain constant.

n_{th} = threshold carrier density

N_{ph} - photon density.
g = overall gain per unit length

$$N_{ph} = \frac{P_s}{V_g (h\nu \, \Gamma \, wd)} \quad \text{— (2)}.$$

w = width of active optical area
d = thickness.
V_g = group velocity.
P_s - optical signal power.

In steady state, $\frac{\partial n(t)}{\partial t} = 0$,

From (1), $R_p = R_{st} + \frac{n}{\tau}$ — (4).

From equations (2), (3) & (4)

$$g = \frac{\frac{J}{qd} - \frac{n_{th}}{\tau}}{V_g N_{ph} + \frac{1}{\Gamma a \tau_p}} = \frac{g_0}{1 + N_{ph}/N_{ph,sat}}.$$

where, $N_{ph,sat} = \frac{1}{\tau a v_g \Gamma}$ = saturation photon density.

So, zero signal (Small signal gain per unit length is given by: $g_0 = \tau a \tau_p \left(\frac{J}{qd} - \frac{n_{th}}{\tau}\right)$.

3. $P_{s,in} \leq \frac{(\lambda_p / \lambda_s) P_{p,in}}{G - 1}$

Max. input power, $P_{s,in} \leq \frac{(980/1550)(30 mW)}{100 - 1} = 190 \mu W$.

Max output power,

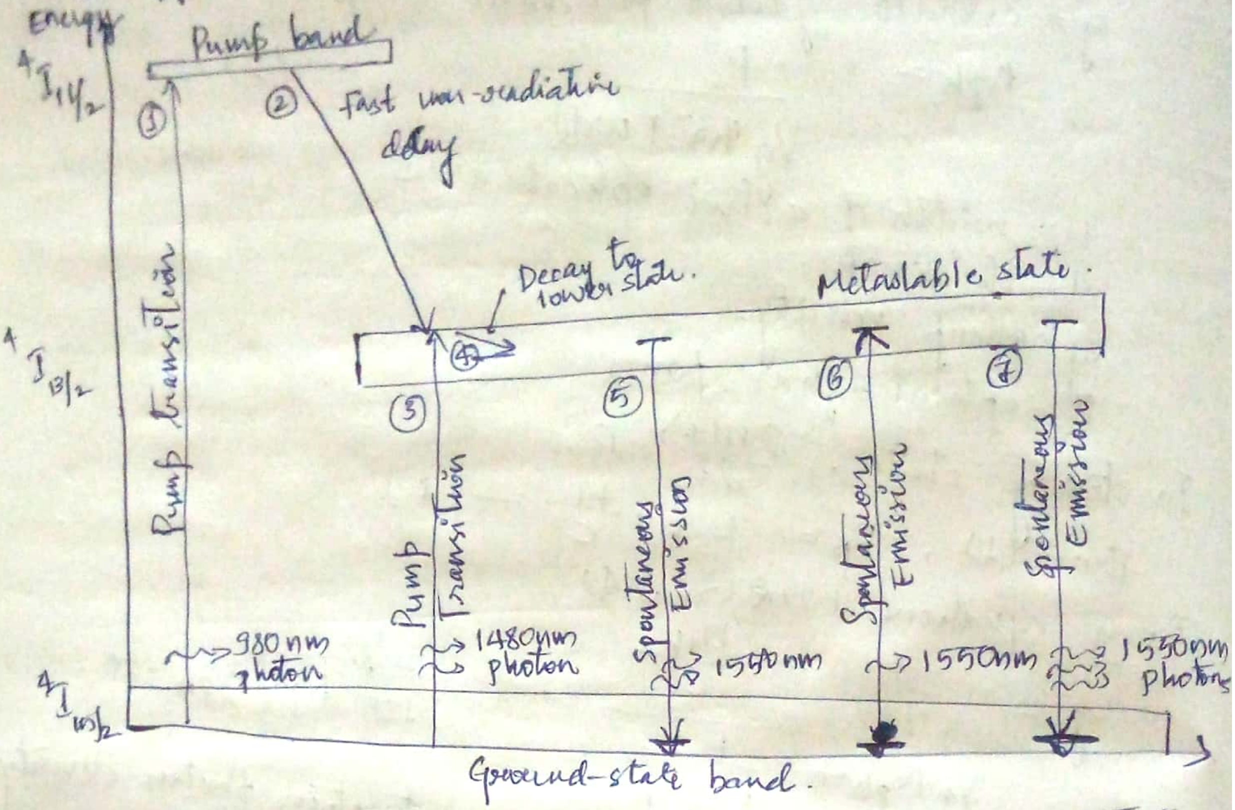
$$P_{s,out}(max) = P_{s,in}(max) + \frac{\lambda_p}{\lambda_s} P_{p,in}$$

$$= 190 \mu W + 0.63 (30 mW)$$

$$= 19.1 mW.$$

In dBm, $10 \log \left(\frac{P_{s,out}}{1 mW}\right) = \cancel{19.8} \; 12.8$ dBm

4. Energy-level diagram:



→ Photons are used to directly raise electrons into excited states.

→ Uses 3 energy levels.

i) Top energy level to which $\bar{e}$ is elevated must lie energetically above desired lasing level (pump level).

ii) From this level, a signal photon can then trigger into stimulated emission, whereby it releases its remaining energy in the form of a new photon with a wavelength identical to that of the signal photon.

Since, the pump photon must have a higher energy than the signal photon, wavelength is shorter than signal wavelength.

EDFA working:

→ Erbium atoms in silica are actual Er^{3+} ions.

Two principal levels for telecommunication applications are-

Metastable level ($^4I_{13/2}$ level)

Pump level ($^4I_{11/2}$ level).

Life times of Transitions from metastable to ground state is very long compared to with the lifetimes of states that led to this level.

In normal operation.

→ Pump laser emitting 980nm photon is used to excite e from ground state to pump level (process 1).

→ These electrons ~~decay~~ decay very quickly (1μs) from pump band to metastable band (process 2)

→ Excess energy is released as photons.

→ within metastable band, the electrons or excited e tend to populate the lower band

● Another possible operation,

→ Pump wavelength of 1480nm. The energy of these pump photons is very similar to the signal photon energy.

→ This excites electron to lightly populated top of metastable level (process 3)

→ These electrons tend to move to ~~low~~ lower end of metastable state (process 4)

* Transitions when signal flux pass through device:

i) Some ions sitting in metastable state, tend to decay back to ground state without any externally stimulating photon (absence) emission (process 5).

thus. this is spontaneous emission process (process 7)

ii) Stimulated emission process (process 7)

iii) External ~~photon~~ ions (photons) will be absorbed by ions in ground state & they rise to metastable state (process 6)

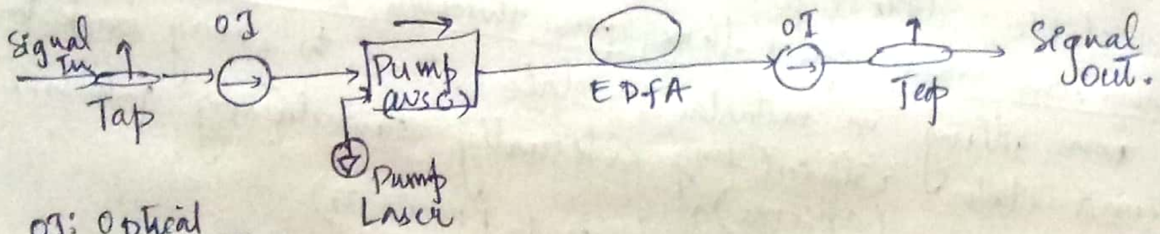
→ The widths of metastable & ground state allows high level of stimulated emissions to occur in the 1530 - 1560nm range. Beyond this gain decreases steadily.

5. Features of SOA:

i) 1310nm, 1400nm, 1550nm, 1610nm wavelength selectable.
ii) Low attenuation windows.
iii) Consume less power, have fewer components & more compact compared to DFAs.
iv) Have rapid response.
v) Can be implemented when both switching & signal processing are called for optical networks.
vi) Gain fluctuations (sometimes).

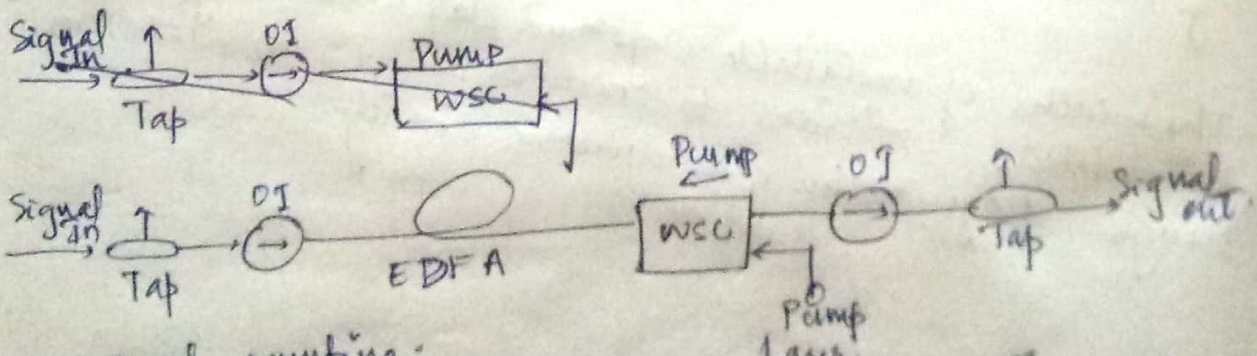
6. Configurations of EDFA:

i) Co-directional pumping: Pump light injected in the same direction as signal flow.

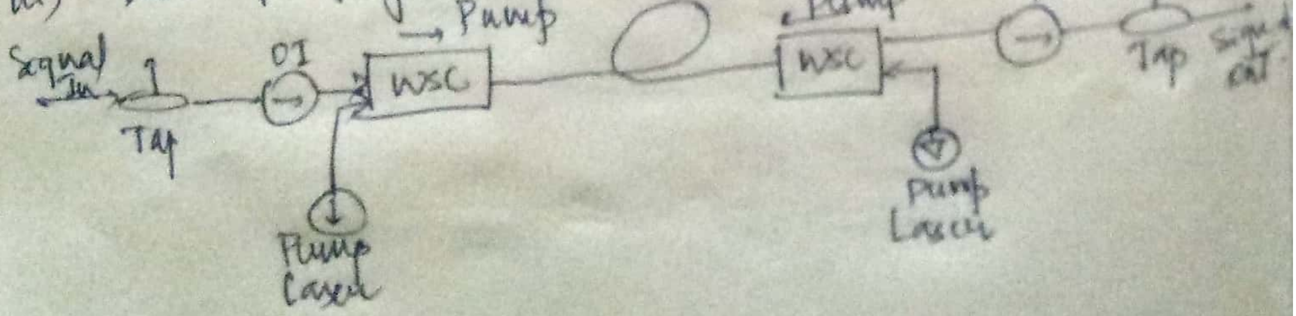


OI: Optical Isolator
WSC: wavelength-selective coupler.

ii) Counter-directional coupling: Pump power injected in the opposite direction to the signal flow.



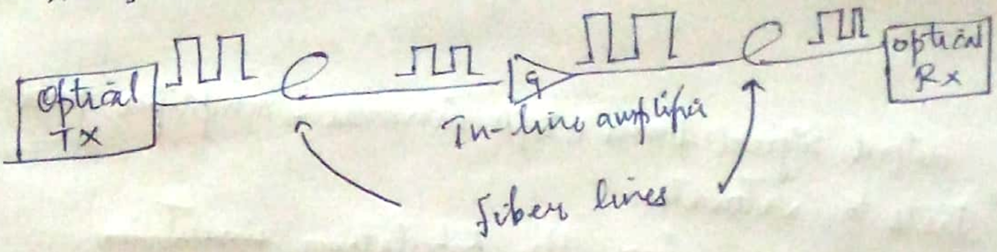
iii) Dual pumping:



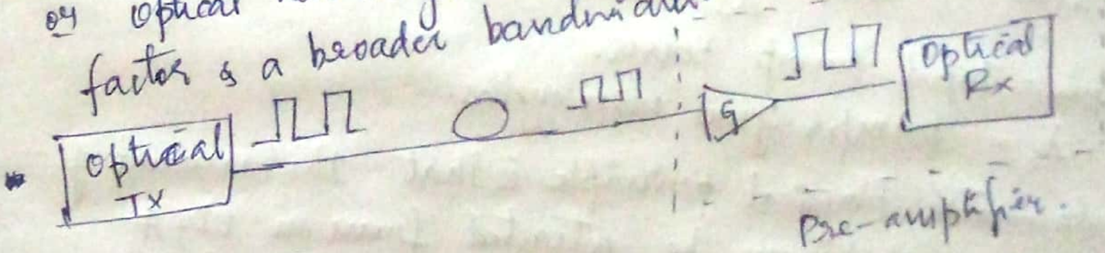
→ Counter directional pumping allows higher gains,
Co-directional pumping gives better noise performance.

7. Applications:

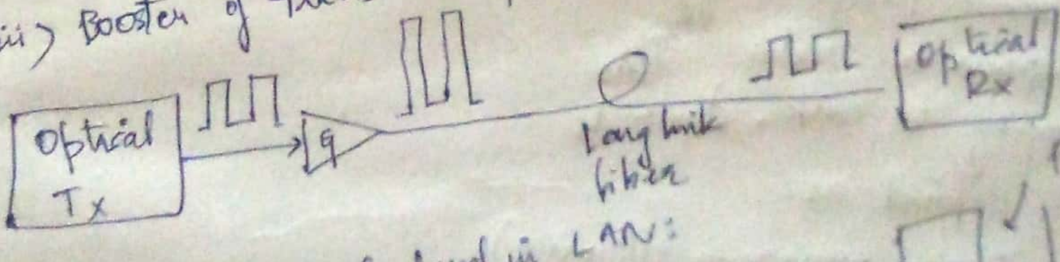
i) Inline amplifiers:
Optical amplifier can be used to compensate for transmission loss & increase the distance between regenerative repeaters.



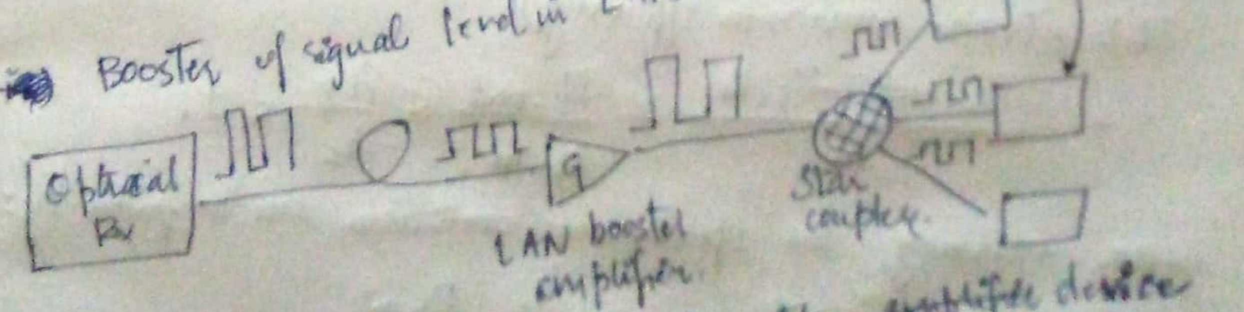
ii) Preamplifiers:
Weak signal is amplified before ~~photodetector~~ photo-detection so that signal-to-noise ratio is suppressed in Rx.
This (optical preamplifier), compared to avalanche photodiodes or optical heterodyne ~~[illegible]~~ detectors has larger gain factor & a broader bandwidth.



iii) Booster of transmitted power:



Booster of signal level in LAN:



This application includes placing the amplifier device immediately after an optical transmitter to boost the transmitted power.

this serves to increase ~~[illegible]~~ transmission distance, ~~[illegible]~~ compensates for coupler-insertion loss & power-splitting loss.

iv) Power amplifiers:

Input power is high, since device immediately follows an optical amplifier.

8. PCE:

Magnitude of output signal from EDFA increases, amplifier gain eventually starts to saturate.

Reduction in gain occurs when the population ~~inversion~~ inversion is reduced significantly by large-signal.

Input & ~~po~~ output powers of an EDFA can be expressed in terms of principle of energy conservation.

$$P_{s,out} \le P_{s,in} + \frac{\lambda_p}{\lambda_s} P_{p,in}.$$

where, $P_{p,in}$ = Input pump power.

λ_p, λ_s = pump & signal wavelengths.

The fundamental physical principle is that the amount of signal energy that can be extracted from an EDFA can't exceed pump energy that is stored in the device.

output depends on ratio λ_p/λ_s.

For pumping to work, $\lambda_p < \lambda_s$.

PCE is defined as,

PCE (Power conversion efficiency)

$$= \frac{P_{s,out} - P_{s,in}}{P_{p,in}} \simeq \frac{P_{s,out}}{P_{p,in}} \le \frac{\lambda_p}{\lambda_s} \le 1.$$

Gain, assuming no spontaneous emission can be given by:

$$G \simeq \frac{P_{s,out}}{P_{s,in}} \le 1 + \frac{\lambda_p}{\lambda_s} \frac{P_{p,in}}{P_{s,in}}.$$

9. $w = 3\mu m.$

$d = 0.3\mu m.$

$L = 500\mu m.$

$\Gamma = 0.3$

$\tau_r = 1ns.$

$a = 2\times10^{-20}\ m^2$

$n_{th} = 1\times10^{24}\ m^{-3}$

Bias current = 100mA.

Pumping rate, $R_p = \frac{J}{qd} = \frac{I}{qdwL}$

$= \frac{0.1}{(1.6\times10^{-19})(0.3\times10^{-6})(3\times10^{-6})(500\times10^{-6})}$

$R_p = 1.39\times10^{33}$ (electrons/m^3)/s.

Zero signal gain, $g_o = \tau_r a\Gamma\left(\frac{J}{qd} - \frac{n_{th}}{\tau_r}\right)$.

$g_o = 0.3(2\times10^{-20}\ m^2\times1\times10^{-9}s)\left[1.39\times10^{33}\ m^{-3}s^{-1} - \frac{1.0\times10^{24}\ m^{-3}}{1.0\times10^{-9}}\right]$

$= 23.4 cm^{-1}.$