1. Derive an equation for amplifier gain in semi-conductor optical amplifier (SOA)

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One of the most important parameters of an optical amplifier is the signal gain or amplifier gain G, which is defined as

$$G = \frac{P_{s,out}}{P_{s,in}} \rightarrow (1)$$

where $P_{s,in}$ & $P_{s,out}$ are the input & output powers respectively. of the optical signal being amplified.

The signal pass gain in the active medium is

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

where Γ is the optical confinement factor in the cavity g_m is the material gain co-efficient $\bar{\alpha}$ is the effective absorption co-efficient of the material in the optical path. L is the amplifier length, and g(z) is the overall gain per unit length.

Eqn (2) shows that the gain increases with device length.

An expression for the gain G as a function of the input power can be derived by examing the gain parameter g(z) in eqn (2). This parameter depends on the carrier density and the signal wavelength

g(z) is given by

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

where,

'g_0 → unsaturated medium gain per unit length in the absence of signal input.'

$P_s(z)$ → Internal signal power at point z.

$P_{amp,sat}$ → amplifier saturation power.

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

$$dP = g(z)\, P_s(z)\, dz \longrightarrow (4)$$

substitute eq^n (3) into eq^n (4) and rearranging terms gives

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

Integrating their eq^n from $z=0$ to $z=L$ yields

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

Defining the single pass gain in the absence of light to be G_0

$$G_0 = \exp(g_0 L)$$

and using eq^n (1), we then have

$$\boxed{G = 1 + \frac{P_{amp,sat}}{P_{x,in}} \ln\left(\frac{G_0}{G}\right)}$$

(1) Discuss the external pumping mechanism used in SOA with necessary mathematical equation.

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External current injection is the pumping method used to create the population inversion needed for having a gain mechanism in SOA. this is similar to the operation of laser diodes.

$$\frac{\partial n(t)}{\partial t} = R_p(t) - R_s(t) - \frac{n(t)}{\tau_r} \rightarrow (1)$$

where,

$$R_p(t) = \frac{J(t)}{qd} \rightarrow (2)$$

is the external pumping rate from the injection current density $J(t)$ into the an active layer of thickness d, τ_r is the combined time constant coming from spontaneous emission and carrier-recombination mechanism and

$$R_{st}(z) = \Gamma a v_g (n - n_{th}) N_{ph}$$
$$= g v_g N_{ph} \longrightarrow (3)$$

is the net stimulated emission rate there, v_g is the group velocity of the incident light. Γ is the optical confinement factor, a is a gain constant, n_{th} is the threshold carrier density, N_{ph} is the photons density and g is the overall gain per unit length. Given that the active area of the optical amplifier has a width w and a thickness d, then for an optical signal of power P_s with photons of energy $h\nu$ and group velocity v_g, the photon density is

$$\boxed{N_{ph} = \frac{P_s}{v_g (h\nu)(wd)}}$$

(3) Consider an EDFA being pumped at 980 nm with a 30mW pump power. If the gain at 1550 nm is 20dB. find the maximum input and output power of the amplifier.

→ Maximum input power is

$$P_{x.in} \le \frac{(980/1550)(30mw)}{100-1}$$

$$P_{x.in} \le 190\,\mu w$$

Maximum output power is

$$P_{x.out(max)} = P_{x.in}(max) + \frac{\lambda_p}{\lambda_x} P_{p.in}$$

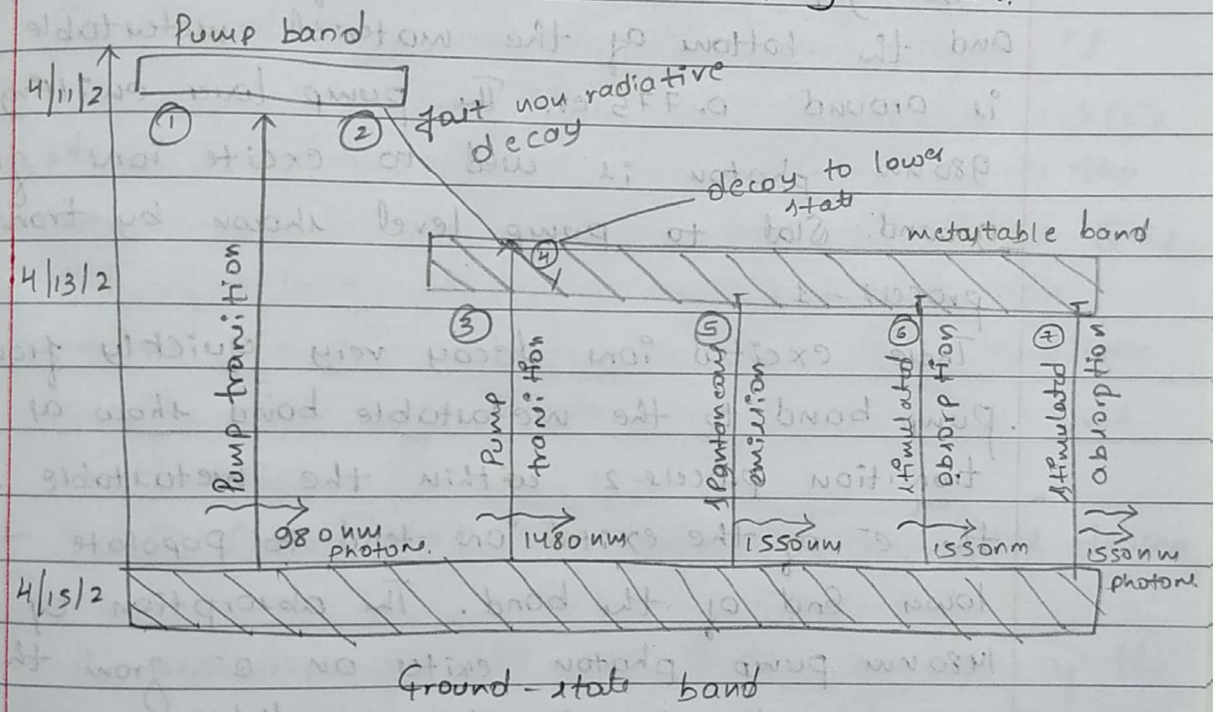
$$= 190\,\mu w + 0.63\,(30mW)$$

$$P_{x.out}(max) = 19.1\,mw$$

$$P_{x.out}(max) = 12.8\,dBm$$

(4) Explain the working of Erbium doped fiber amplifier using Energy level diagrams.

→ The most popular matier used for tellcommunication The most application is a silica fiber doped with erbium medium in an known as EDFA. The active medium in an optical fiber amplifier. Consists of a nominally 10 to 30m length of optical fiber that has been lightly doped with a rare earth element. The operating region of these devices depends on the host material and the doping element.



The Erabium atoms in silica are actual Er^{3+} ions, which are Erbiums atoms that hence lost three of their atoms e^-. the transition of the outer e^- in these ions to higher energy states, it is common to refer to the process as "raising the ion to higher energy levels". The 2 principle level are at metastable state. the pump, and the ground state levels are actually bands of closely spaced energy levels that form a manifold due to the effect known as stark spliting. further each stark level is broadered by

thermal effects into continuous band.
The metastable band is seperated from the bottom of the 4|15/2 ground-state level by an energy gap ranging from about 0.814 eV at the bottom of the metastable band to 0.814 eV at the top. the energy level for pump level exists at a 1.27 eV seperation from the ground state. The pump band is fairly narrow, So that the pump band wavelength must for equal to within a few nano meters.
The gap between the top of the 4|15/2 level and the bottom of the material metastable band is around 0.775 eV. The pump laser emitting 980 nm photon is used to excite ions from ground. Stat to pump level shown by transition process - 1.
These excited ions decay very quickly from the pump band to the metastable band show as transition process-2 within the metastable state the e⁻ of the exited ions tend to populate the lower end of the band. The absorption of 4 1480 nm pump photon excites an e⁻ from the ground state directly to the lightly populated top of the metastable level.
These e⁻ than tend to movedown to the more populated lower end of meto stable level (transition 4).
Some of the e⁻ decay back to ground state in the distance of simulated Photon (transition 5).
An absorbed ions raises these ions to the metastable (transition 6). In the simulated emission process (transition 7) a signal photons trigger an exited ion to drop to ground State.

(5) Discuss the salient features of semiconductor optical amplifier.

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* 1310 nm, 1400 nm, 1550 nm and 1610 nm wavelength selectable.
* A high fiber - to - fiber gain of 20 dB
* up to 16 dBm output
* 1 MHz with 10ns pulse width
* PM Panda fiber input / output
* Similar to lasers, but with non - reflecting Ends and broad wavelength emission
* Incoming optical signal stimulates emission of light at its own wavelength.
* The process continues through the cavity to amplify the signal.
* small size can be integrated
* High gain (> 30 dB)
* low dependence of signal polarization (1dB)
* Non - linear properties on saturation
* High Energy Consumption per bit
* phase noise.
* Semiconductor optical amplifiers are typically made from group III - V compound semiconductors such as GaAs / AlGaAs, InP / InGaAs, InP / In GaAsP and InP / InAlGaAs.
* operating signal wavelengths b/w 850 nm & 1600 nm and generating gains of up to 30dB
* SOA has higher noise, lower gain & high non linearity with fast transient time.

⑥ Explain three possible configuration of a EDFA.

→ Three possible configuration of a EDFA are Amplifier noise, power conversion Efficiency and gain saturation and Gain spectrum.

Amplifier noise :-

The dominant noise generated in an optical amplified is amplified Spontaneous Emission. EDFA amplifying a Signal at 1540 nm.

The power Spectral density of ASE noise is.

$$S_{ASE}(f) = h\nu n_{sp}[G(f)-1] = P_{ASE}/\Delta\nu_{opt} \rightarrow (1)$$

where, P_{ASE} = ASE noise power in an optical BW.

$\Delta\nu_{opt}$ & n_{sp} = Spontaneous Emission.

popular inversion factor is defined as.

$$n_{sp} = \frac{n_2}{n_2 - n_1} \longrightarrow (2)$$

where, n_1 & n_2 are the factorial densities.

from Eq^n (2), $n_{sp} \geq 1$.

with equality holding for an ideal amplifier when the population inversion is complete.

If the total optical field is the sum of the signal field E_s & the spontaneous emission field E_n. then the total photodetector current i_{tot} is proportional to the square of the electric field of the optical signal.

$$i_{tot} \propto (E_x + E_n)^2 = E_s^2 + E_n^2 + 2E_x \cdot E_n.$$

optical power incident on the photo detector becomes

$$P_0 = GP_{s,in} + S_{ASE}\,\Delta\nu_{opt}.$$

The total mean-square shot-noise current

$$\langle i^2_{shot}\rangle = a^2_{shot} = a^2_{shot-s} + a^2_{shot-ASE}$$

$$= 2qRGP_{s,in}B + 2qRS_{ASE}\cdot\Delta\nu_{opt}B \rightarrow (3)$$

Beat noise of the signal with ASE is

$$\sigma^2_{S-ASE} = 4(RGP_{s.in})(RS_{ASE}B) \rightarrow (4)$$

$$\sigma^2_{ASE-ASE} = R^2S^2_{ASE}(2\Delta V_{opt} - B)B \rightarrow (5)$$

total mean-square receiver noise current that becomes

$$(i^2_{total}) = \sigma^2_{total} = \sigma^2_{T} + \sigma^2_{shot-s} + \sigma^2_{shot-ASE} + \sigma^2_{S-ASE} + \sigma^2_{ASE-ASE} \rightarrow (6)$$

thermal noise variance σ^2_T is given in Eq^n.
This observation reduces Eq^n,

$$\sigma^2_{shot} = 2qRGP_{s.in}B. \rightarrow (7)$$

$$\left(\frac{S}{N}\right)_{out} = \frac{\sigma^2_{ph}}{\sigma^2_{total}} = \frac{R^2G^2P^2_{s.in}}{\sigma^2_{total}} \approx \frac{RP_{s.in}}{2qB} \cdot \frac{G}{1+2\eta n_{sp}(G-1)} \rightarrow (8)$$

the mean square i/p photocurrent is

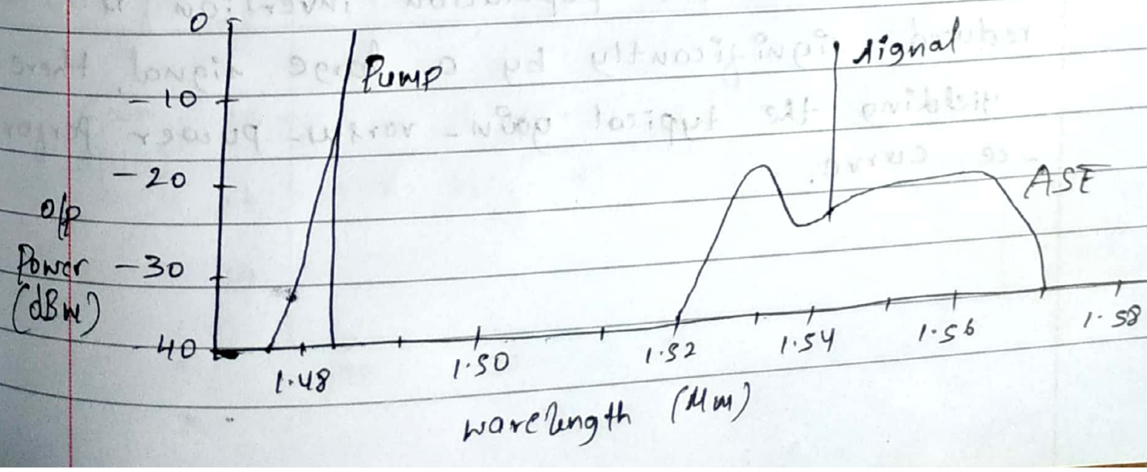
$$(i^2_{ph}) = \sigma^2_{ph} \approx R^2G^2P^2_{s.in} \rightarrow (9)$$

Note that the term,

$$\left(\frac{S}{N}\right)_{in} = \frac{RP_{s.in}}{2qB} \rightarrow (10)$$

$$\text{Noise figure} = F = \frac{(S/N)_{in}}{(S/N)_{out}} = \frac{1+2\eta n_{sp}(G-1)}{\eta G} \rightarrow (11)$$

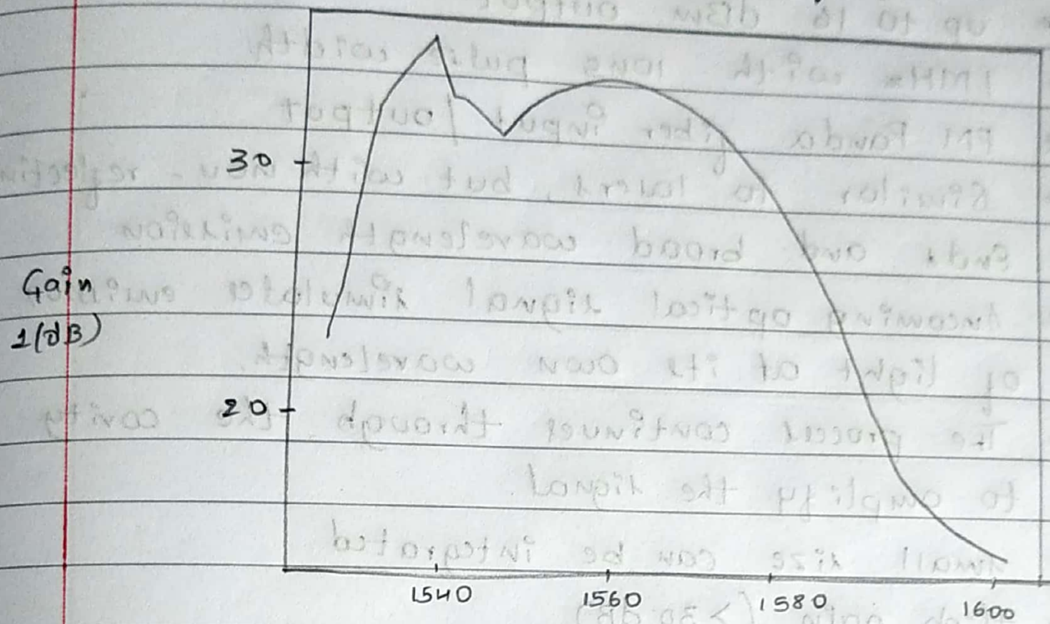
when G is large, this becomes $2\eta n_p$.
A perfect amplifier would have $n_{sp}=1$, yielding a noise figure of 2 or 3dB.



Gain spectrum :-

The signal wave length of the CW laser signal is swept from 1525 nm to 1600 nm, which Enables evaluating the spectral gain and the BW of the amplifier.

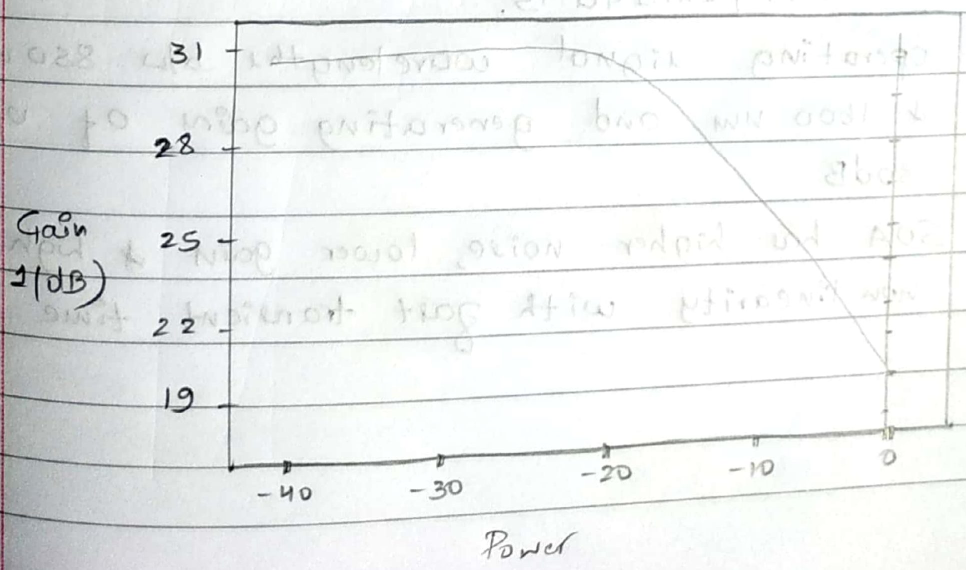
Gain 1(dB) vs. frequency.



Gain saturation :-

The layout Gain saturation Enables evaluating the amplifier Performance as a function of the signal input power. The amplifier performance given by gain, o/p power & noise figure.

Gain 1(dB) vs. power.



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(7) Name the four possible application of optical amplifier and explain each of them with figure.

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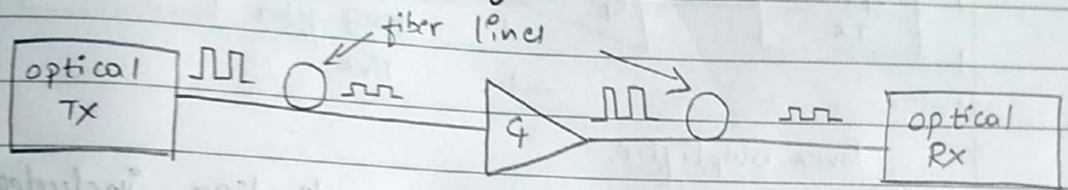
Application of optical amplifier are :-

* In-Line optical amplifier
* Pre amplifier
* Power amplifier.

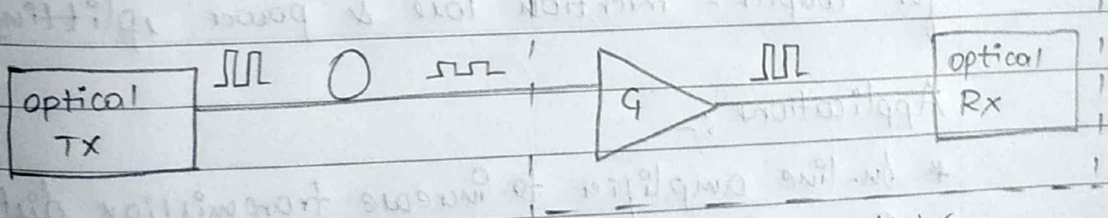
In-line optical amplifier :-



In-line amplifier

In a single mode link the effects of fiber dispersion may be small so that the main limitation to repeater spacing is fiber attenuation.
Such a link does not neccessaryily require a Complete regeneration of the signal.
Simple simplication of the optical signal is sufficient the optical amplifier is sufficient the optical amplifier. can be used to compensate for transmission loss & increase the distance between regenrative repeater.

Pre amplifiers :-



Pre-amplifier

It is used as a front end preamplifier for an optical receiver. A weak optical signal is amplified before

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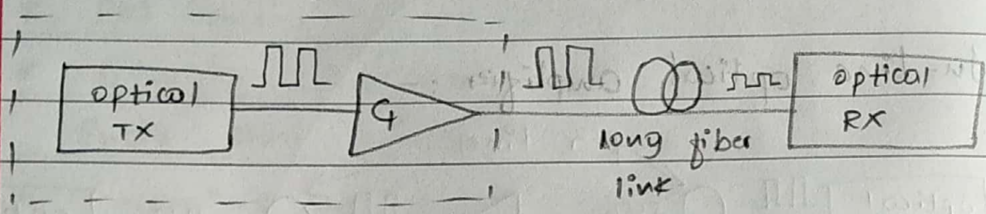
photo detection. so that the SNR degradation caused by thermal noise in the receiver Electronic can be supressed. Compare with other front end amplifiers such as avalanche photodiodes or optical heterodyne detector. It provides a target gain factor & a broded bandwidth.

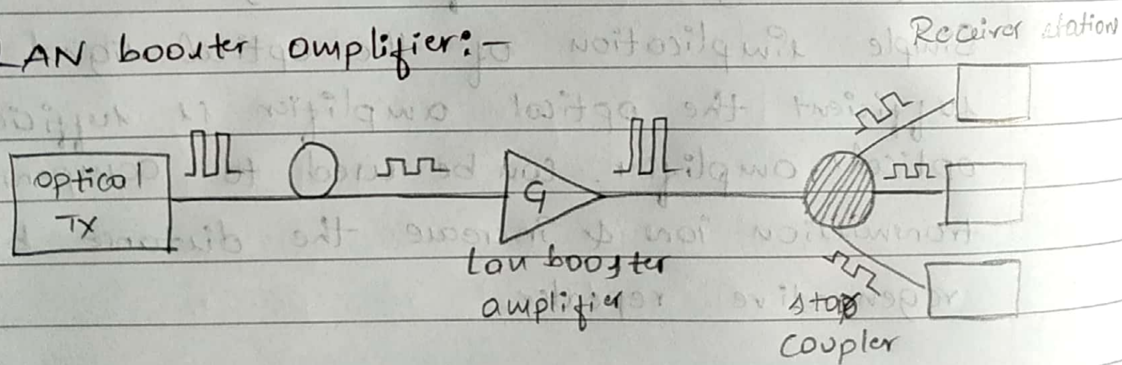
Power amplifier:-



Power amplifier.

power or booster amplifier application includes placing the device immedeately after an optical transmission to boost the transmitted power. this serve to increase the transmission distortion by 10-100 km depending on the amplifier gain fiber loss.

LAN booster amplifier:-



Local area network as a booster amplifier to complete for coupler - insertion loss & power splitting loss.

Applications :-

* In-line amplifier to increase transmission distance
* Pre amplifier to improve receiver senitivity
* Booster of transmitted power
* Booster of signal level in a local area network

(8) Illustrate the power conversion Efficiency & Gain in EDFA.

→ Power Conversion efficiency & Gain :-

The i/p & o/p power of an EDFA can be Expressed in terms of the principle of Energy Conservation.

$$P_{s,out} \leq P_{s,in} + \frac{\lambda_p}{\lambda_s} P_{p,in} \rightarrow (1)$$

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

λ_p & λ_s = pump & signal wavelength.

Thus power conversion Efficiency defined as,

$$PCE = \frac{P_{s,out} - P_{s,in}}{P_{p,in}} \approx \frac{P_{s,out}}{P_{p,in}} \leq \frac{\lambda_p}{\lambda_s} \leq 1 \rightarrow (2)$$

Quantum-efficiency Conversion is defined by,

$$QCE = \frac{\lambda_s}{\lambda_p} PCE \rightarrow (3)$$

there is no spontaneous emission, then

$$G = \frac{P_{s,out}}{P_{s,in}} \leq 1 + \frac{\lambda_p}{\lambda_s} \frac{P_{p,in}}{P_{s,in}} \rightarrow (4)$$

The input signal power cannot exceed a value given by

$$P_{s,in} \leq \frac{(\lambda_p / \lambda_s) P_{p,in}}{G-1} \rightarrow (5)$$

In this case with any amplifier, as the magnitude of the output signal grow EDFA increase the amplifier gain eventually stars to saturate. the reduction of gain in an EDFA occurs when the population inversion is reduced significantly by a large signal, thereby yielding the typical gain-versus-power performance curve.

(9) Consider an InGaAsP SOA that has cavity dimensions,

→ Active area width (w) = $3\,\mu m$

→ Active area thickness (d) = $0.3\,\mu m$ and

→ Amplifier length (L) = $500\,\mu m$

Assume the SOA has a

→ Confinement factor (Γ) = 0.3

→ Time Constant (τ) = 1ns

→ Gain co-efficient (a) = $2\times10^{-20}\,m^2$

→ Threshold density (n_{th}) = $1\times10^{24}\,m^{-3}$

If a 100mA bias current is applied to the device, determine the pumping rate & zero signal gain for the SOA

→ If a 100 mA bias current is applied to the device, the pumping rate is

$$R_p = \frac{J}{qd} = \frac{I}{qdwL}$$

$$= \frac{0.1A}{(1.6\times10^{-9}\,C)(0.3\,\mu m)(3\,\mu m)(500\,\mu m)}$$

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

the zero-signal gain is

$$R_0 = 0.3\,(2.0\times10^{-29}\,m^2)(1ns)\left(1.39\times10^{33}\,m^{-3}s^{-1} - \frac{1.0\times10^{24}\,m^{-3}}{1.0ns}\right)$$

$$R_0 = 2340\,m^{-1}$$

$$R_0 = 23.4\,cm^{-1}$$