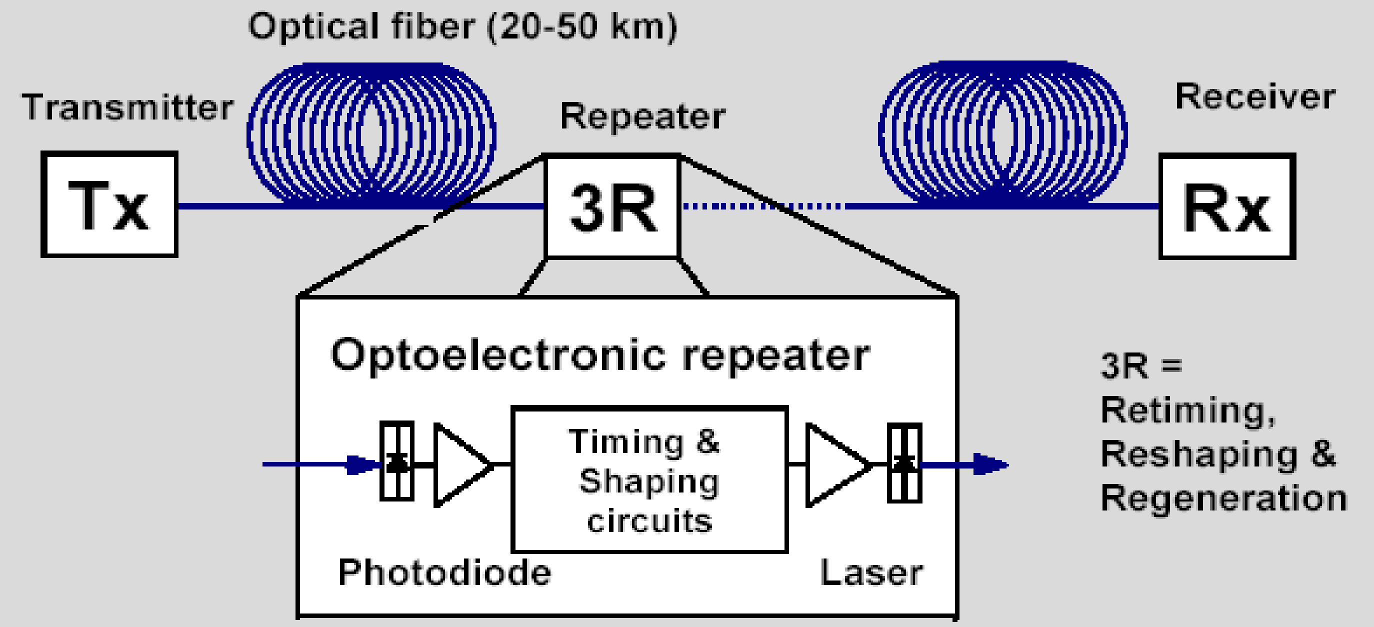
Optical Amplifiers

An Important Element of WDM Systems

Optical Amplifiers

- Conventional Repeaters in N-WDM systems are very inefficient:
  - Wavelength de-multiplexing →
  - O/E conversion → electrical amplification → retiming → pulse shaping → E/O conversion} N - times
  - wavelength multiplexing
- Optical Amplifiers: A single device that amplify multiple format signals that are carried by multiple wavelengths

Traditional Optical Communication System

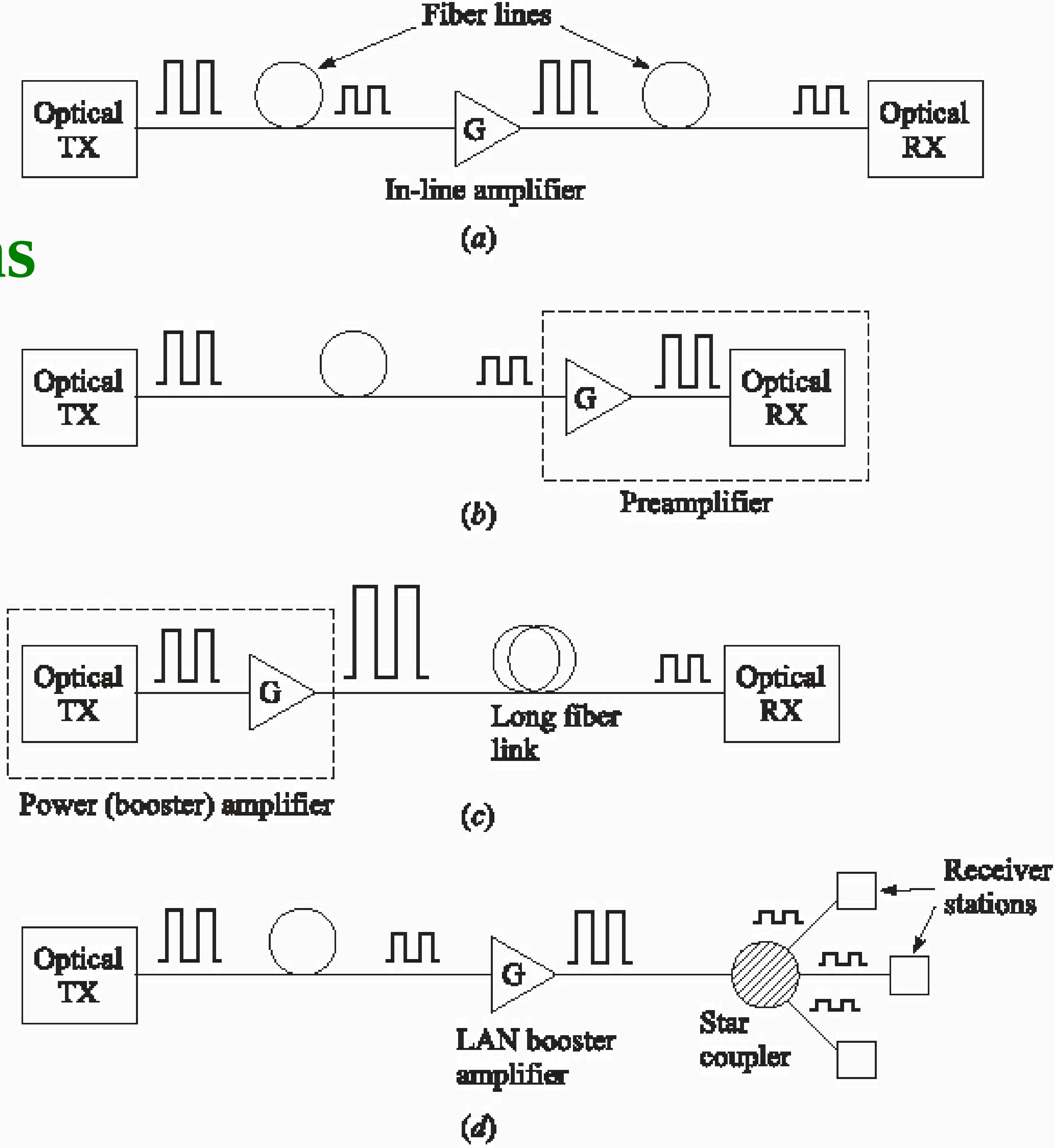


System capacity limited by speed of electronic circuits

Optical Amplification

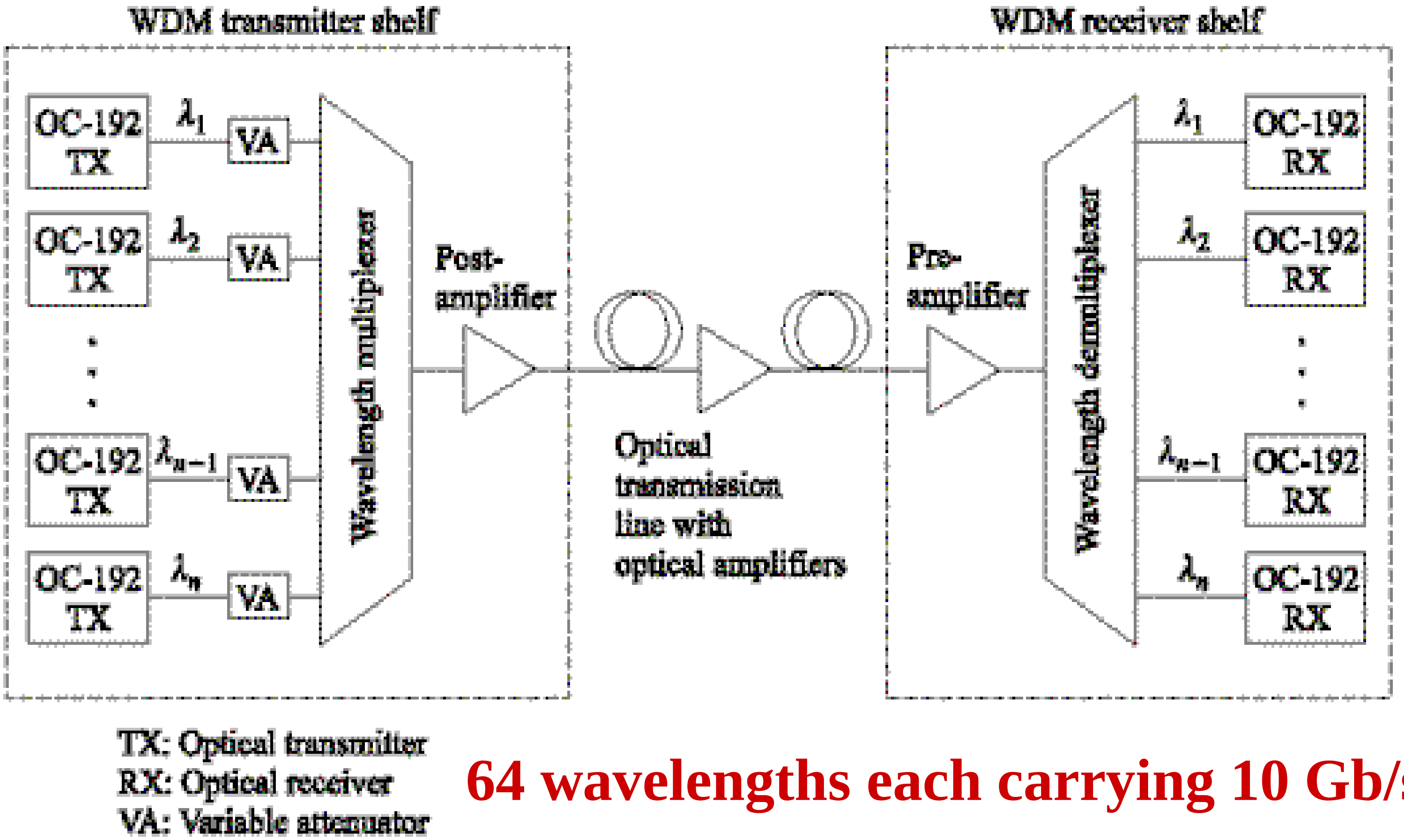
- Variety of optical amplifier types exist, including:
  - Semiconductor optical amplifiers
  - Optical fibre amplifiers (Erbium Doped Fibre Amplifiers)
  - Distributed fibre amplifiers (Raman Amplifiers)
- Optical fibre amplifiers are now the most common type
- One of the most successful optical processing functions
- Also used as a building block in DWDM systems

Applications



Power Amp Configurations

Nortel OPTERA System

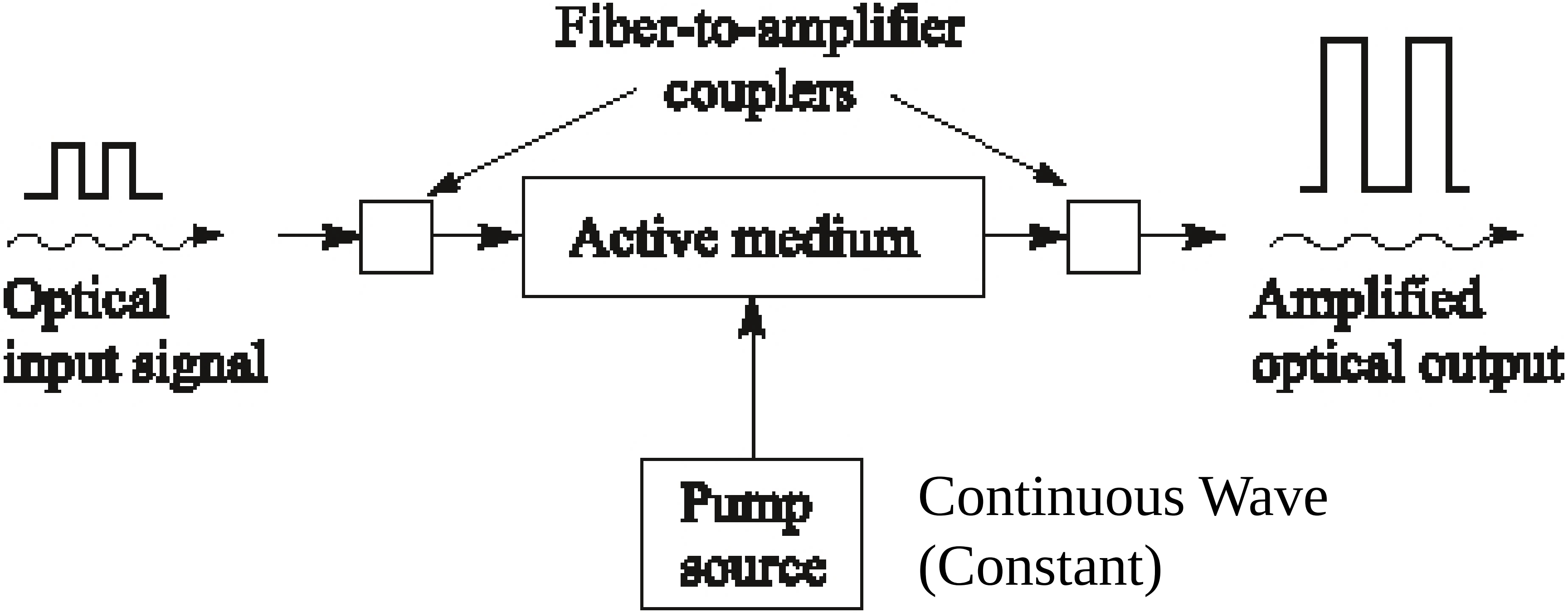


64 wavelengths each carrying 10 Gb/s

Basic Concepts

- Most optical amplifiers use stimulated emission
- An optical amplifier is basically a laser without feedback
- Optical gain is realized when the amplifier is pumped optically (or electrically) to achieve *population inversion*
- Gain depends on wavelength, internal light intensity and amplifier medium
- Two types: semiconductor optical amplifiers and fiber doped amplifiers

Generic optical amplifier



Continuous Wave
(Constant)

Energy is transferred from the pump to signal

Semiconductor Optical Amplifiers

- Similar to Laser diodes but the emission is triggered by input optical signal
- Work in any wavelength (+)
- Have high integration, compact and low power consumption (+)
- Gain fluctuation with signal bit rate (-)
- Cross talk between different wavelengths (-)
- External Current injection pumping method
- Two types: Fabry-Perot or Traveling Wave Amp.

External Pumping

Current injection -> ext. pumping => to amplify optical signals via stimulated emission=> PI

Rate equation

stimulated emission

carrier density in excited state

$$\frac{\partial n(t)}{\partial t} = R_p(t) - R_{st}(t) - \frac{n(t)}{\tau_r}$$

external pumping rate

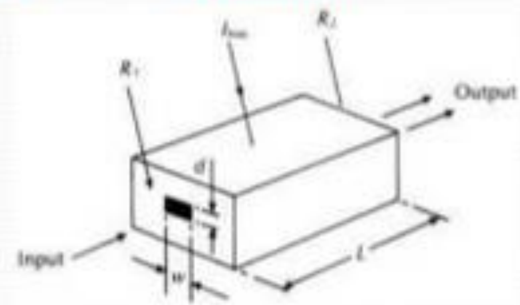
combined time constant coming from spontaneous-carrier recombination mechanism

current density

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

thickness of active area

charge carrier



group velocity

threshold carrier density

photon density

$$R_{st}(t) = \Gamma a v_g (n - n_{th}) N_{ph} \equiv g v_g N_{ph}$$

gain constant

overall gain per unit of length

optical confinement factor

power of optical signal

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

energy of photon

width of active area

Under steady state condition, variation of n vs time is zero, therefore:

$$R_p = R_{st} + \frac{n}{\tau_r}$$

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

$$\boxed{R_{st}(t) = \Gamma a v_g (n - n_{th}) N_{ph} \equiv g v_g N_{ph}}$$

Gain is increased with increasing current injection

$$\boxed{g = \frac{\dfrac{J}{qd} - \dfrac{n_{th}}{\tau_r}}{v_g N_{ph} + 1/(\Gamma a \tau_r)} = \frac{g_0}{1 + N_{ph}/N_{ph;sat}}}$$

Gain is saturated with increasing photon density

$$\boxed{N_{ph;sat} = \frac{1}{\Gamma a v_g \tau_r}}$$

Saturation photon density

$$\boxed{g_0 = \Gamma a \tau_r \left(\frac{J}{qd} - \frac{n_{th}}{\tau_r} \right)}$$

g_o is the zero or small-signal gain

per unit of length (in the absence of the signal input)

Amplifier Gain

Amplifier gain , $G = \frac{P_{s,out}}{P_{s,in}}$

$P_{s,in}$ = Input power of optical signal

$P_{s,out}$ = Output power of amplified optical signal

Same as that of LASER,

$G = e^{(\Gamma g_m - \bar{\alpha})L} = e^{(g(z))L}$

Where,

- G = single pass gain in active medium of SOA
- gm = The material gain coefficient
- α = Effective absorption coefficient of the material
- L = Amplifier length respectively

g(z) = overall gain per unit of length

(depends on the carrier density & s/l wavelength)

From the eqn,

G, gain ↑ with device length & the internal gain is limited by gain saturation.

i/p power ↑ => G ↑ => EHP depleted from the active region => will not have enough EHP in the active region to be stimulated=> gain saturation

large optical input => Gain saturates

g(z) can written as $\boxed{\dfrac{g_0}{1+\dfrac{P_S(Z)}{P_{amp,sat}}}}$

g_0= unsaturated medium gain per unit of length in the absence of signal input

$P_S(z)$ = internal signal power at point z.

$P_{amp,sat}$ = amplifier saturation power

The increase in the light power in incremental length of dz can be expressed as:

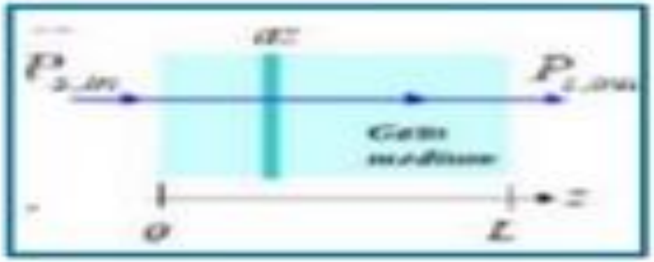
$$\boxed{dP = g(z)\, P_s(Z)dz = \frac{g_0}{1+\frac{P_S(Z)}{P_{amp.sat}}} P_S(z)\, dz}$$

Solving for g_0.

$$g_0 dz = dP\left\{1 + \frac{P_S(Z)}{P_{amp.sat}}\right\}\frac{1}{P_S(Z)}dz$$

$$g_0 dz = dP\left\{\frac{1}{P_S(Z)} + \frac{P_S(Z)}{P_S(Z)\, P_{amp.sat}}\right\} dz$$

$$g_0 dz = dP\left\{\frac{1}{P_S(Z)} + \frac{1}{P_{amp.sat}}\right\} dz$$



Now integrating both sides with

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

$$\int_0^L g_0 \mathrm{dz} = g_0 \int_0^L \mathrm{dz} = g_0[z]_0^L = g_0[L - 0] = g_0 L \dots\dots\dots ()$$

$$\int_{P_{s,in}}^{P_{s,out}} \left\{\frac{1}{P_S(Z)} + \frac{1}{P_{amp.sat}}\right\} dz$$

$$=> \int_{P_{s,in}}^{P_{s,out}} \left\{\frac{1}{P_S(Z)}\right\} dz + \int_{P_{s,in}}^{P_{s,out}} \left\{\frac{1}{P_{amp.sat}}\right\} dz$$

$$= [lnP_S(Z)]_{P_{s,in}}^{P_{s,out}} + \frac{1}{P_{amp.sat}} [z]_{P_{s,in}}^{P_{s,out}}$$

$$= \ln(P_{s,out}) - ln(P_{s,in}) + \{\frac{P_{s,out} - P_{s,in}}{P_{amp.sat}}\}$$

$$\ln\left(\frac{P_{s.out}}{P_{s.in}}\right)+\left\{\frac{P_{s.out}-P_{s.in}}{P_{amp.sat}}\right\}=g_0L$$

$$single\ pass\ gain\ in\ absence\ of\ light = e^{(g_0L)}$$

$$\ln(G)+P_{s.in}\left\{\frac{\frac{P_{s.out}}{P_{s.in}}-1}{P_{amp.sat}}\right\}=\ln(G_0)$$

$$\Rightarrow\left\{\frac{G-1}{\frac{P_{amp.sat}}{P_{s.in}}}\right\}=\ln(G_0)-\ln(G)$$

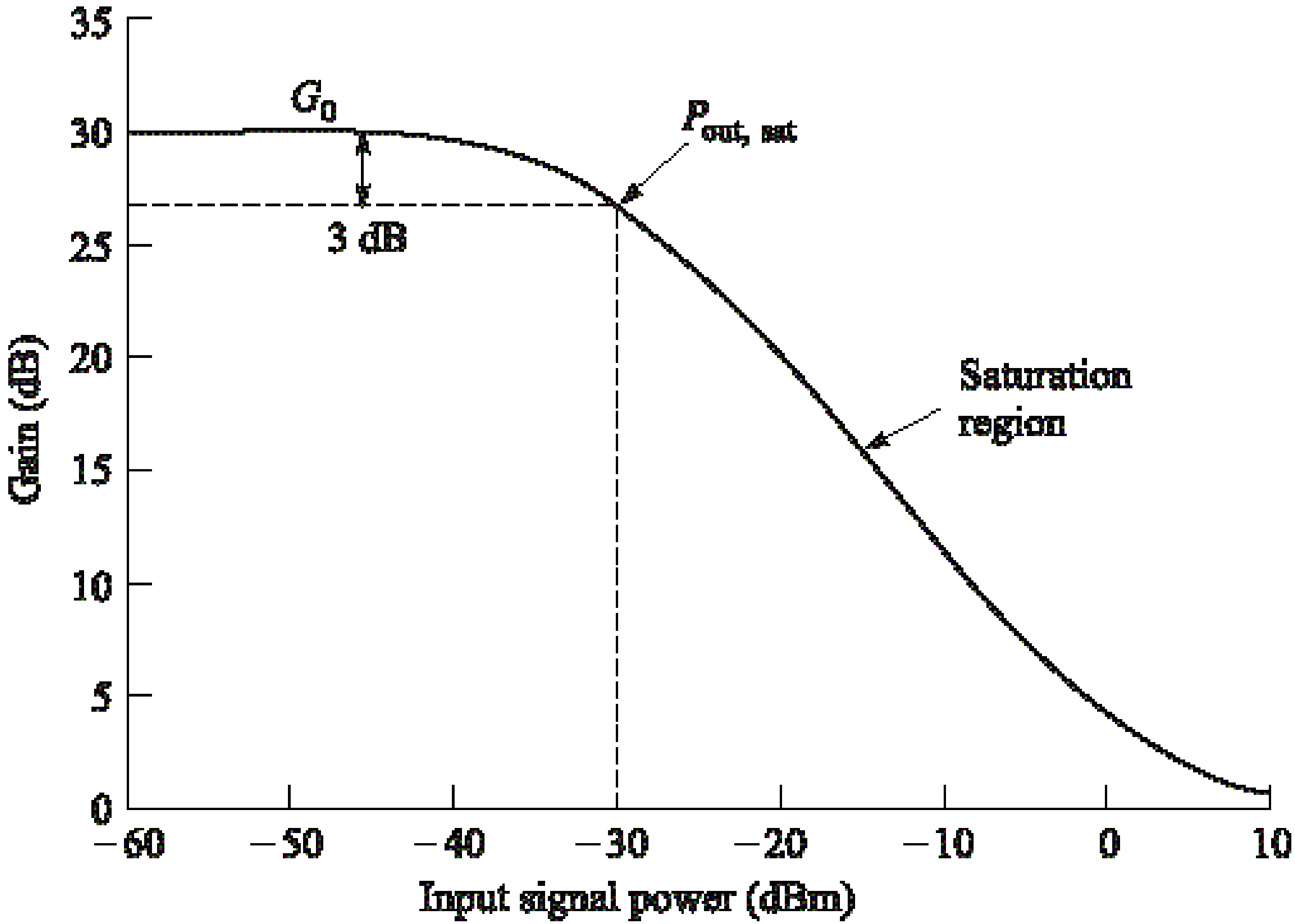
$$\Rightarrow\left\{\frac{G-1}{\frac{P_{amp.sat}}{P_{s.in}}}\right\}=\ln\left(\frac{G_0}{G}\right)$$

Solving for G.

$$\Rightarrow G-1=\ln\left(\frac{G_0}{G}\right)\left\{\frac{P_{amp.sat}}{P_{s.in}}\right\}$$

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

Solid State Amplifier Gain versus Power

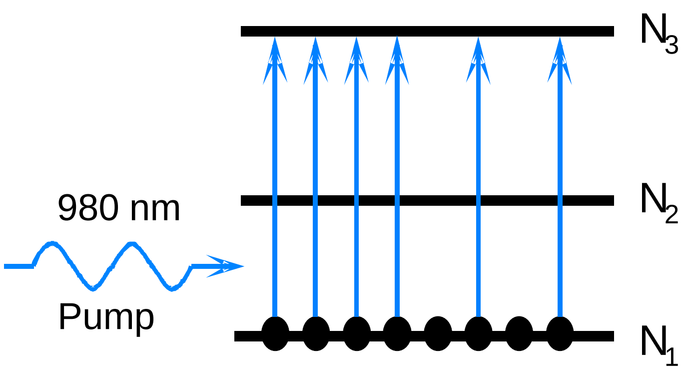


Distributed Fiber Amplifiers

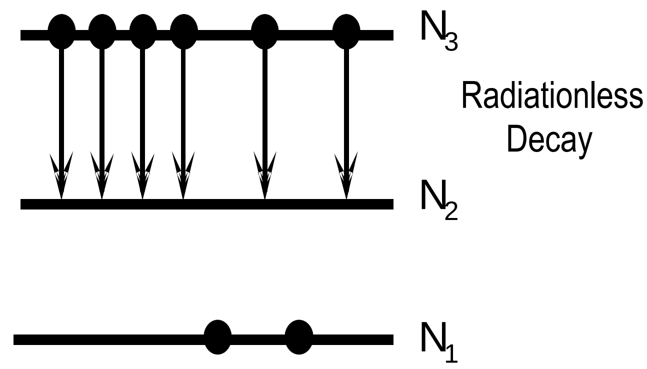
- The active medium is created by lightly doping silica fiber core by rare earth element Ex: Erbium (Er)
- Long fiber length (10-30 m)
- Low coupling loss (+)
- Transparent to signal format and bit rate
- No cross talk
- Broad output spectrum (1530 – 1560 nm)

Works only in specific Wavelengths

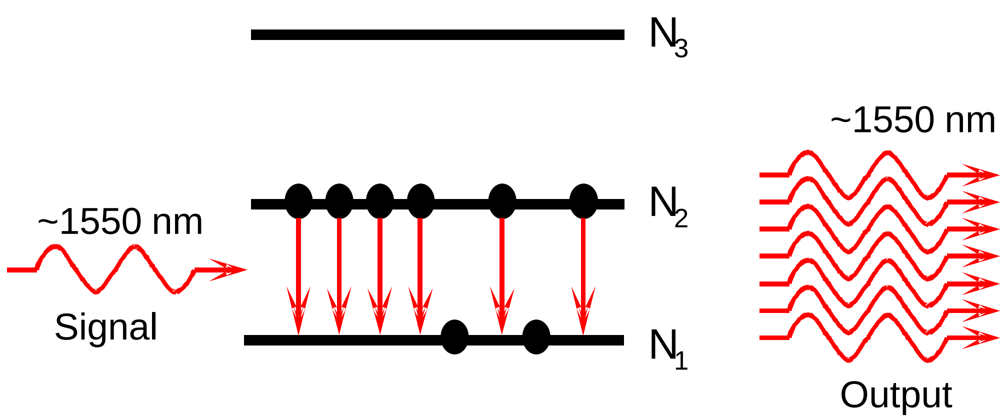
Amplification Process of EDFA



Optical Pumping to Higher Energy levels

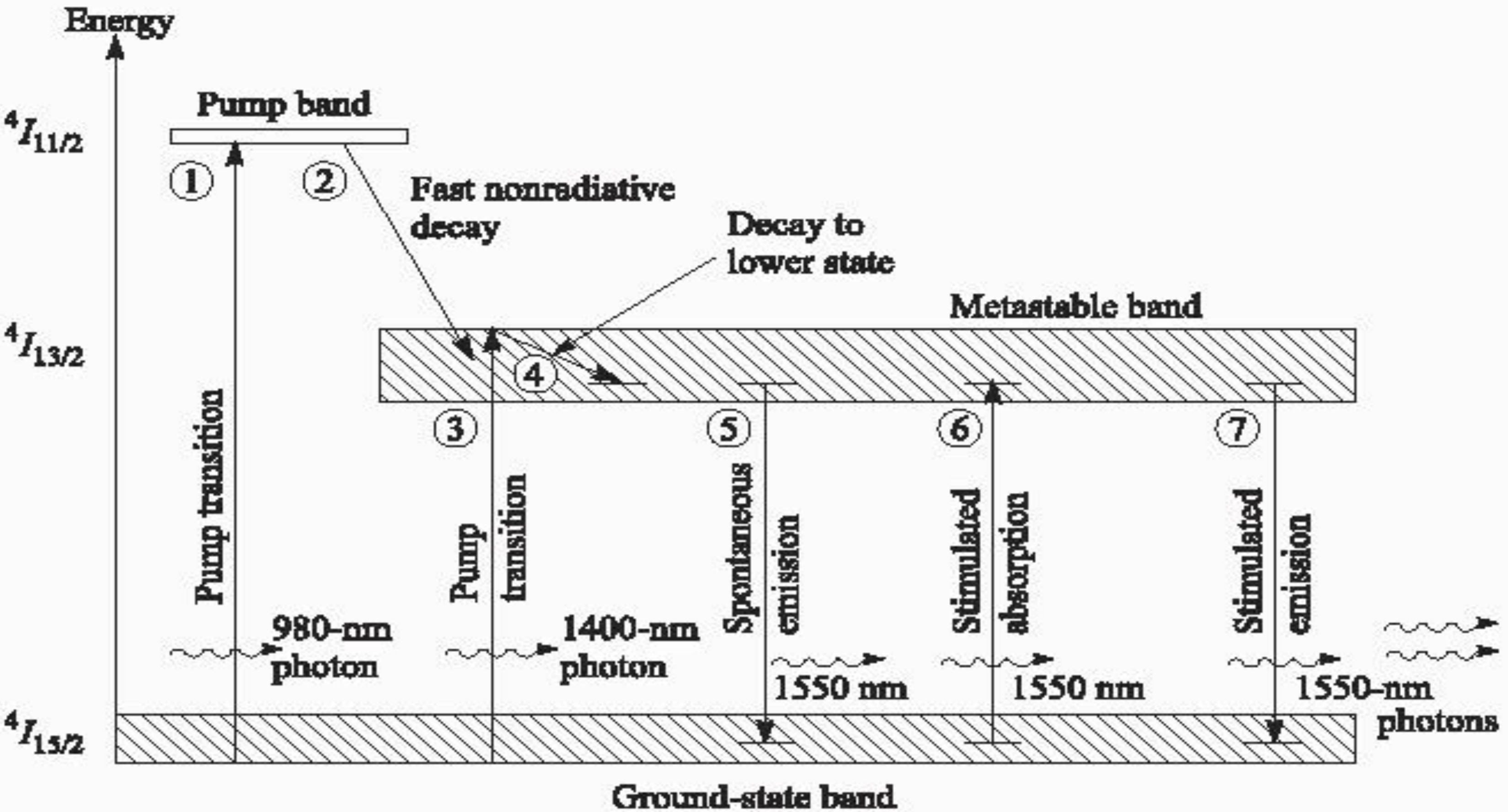


Rapid Relaxation to "metastable" State

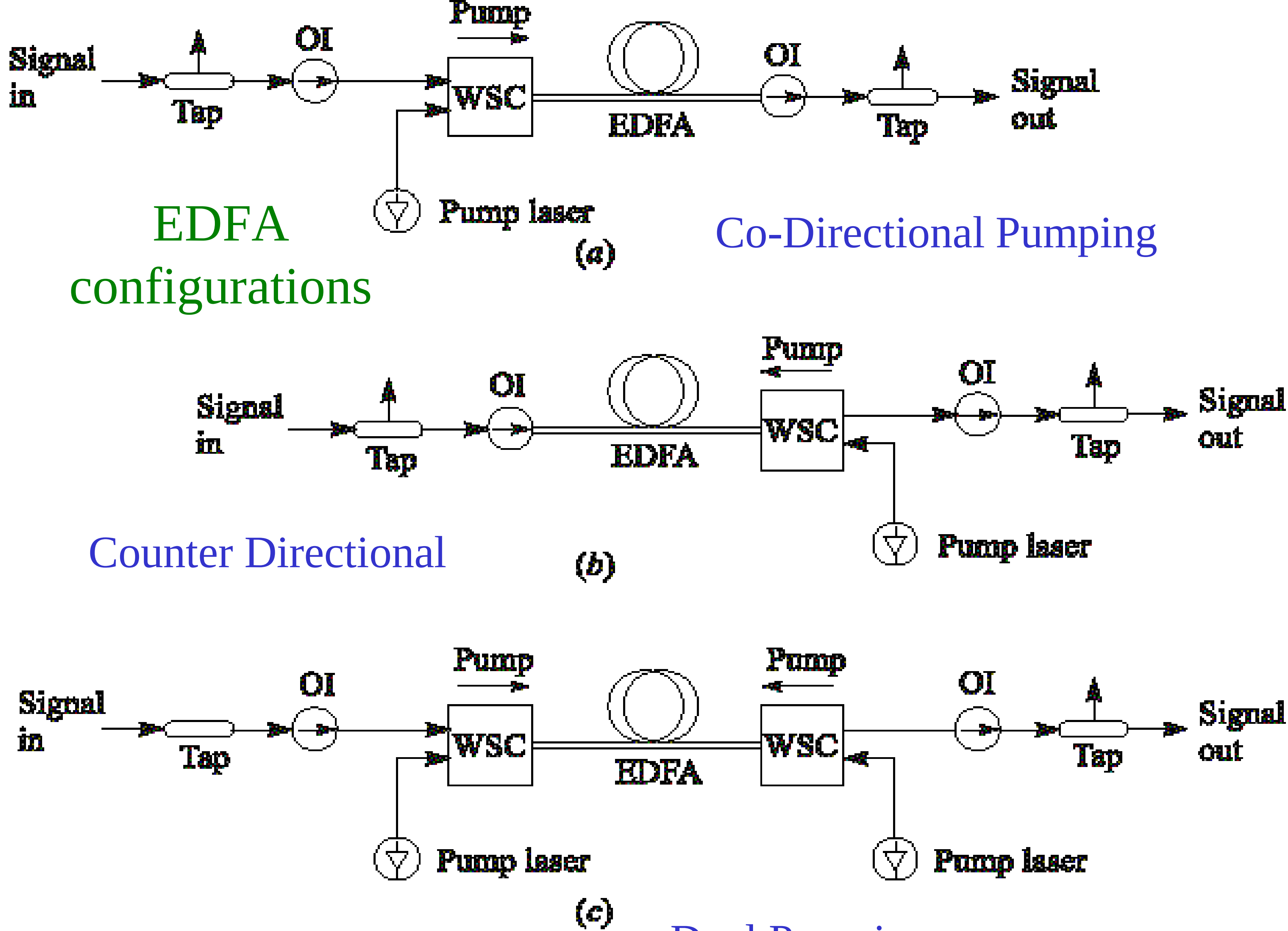


Stimulated Emission and Amplification

Fig. 11-4: Erbium energy-level diagram



EDFA configurations



Co-Directional Pumping

Counter Directional

Dual Pumping

OI: Optical isolator
WSC: Wavelength-selective coupler

EDFA Power-Conversion Efficiency and Gain

- The input and output signal powers of an EDFA

$$P_{s,\mathrm{out}} \leq P_{s,\mathrm{in}} + \frac{\lambda_p}{\lambda_s} P_{p,\mathrm{in}}$$

maximum output signal power depends on the ratio λp/λs. For the pumping scheme to work, we need to have λp < λs, and, to have an appropriate gain, it is necessary that Ps,in ≤ Pp,in. Thus, the power conversion efficiency (PCE), defined as

$$\mathrm{PCE} = \frac{P_{s,\mathrm{out}} - P_{s,\mathrm{in}}}{P_{p,\mathrm{in}}} \approx \frac{P_{s,\mathrm{out}}}{P_{p,\mathrm{in}}} \leq \frac{\lambda_p}{\lambda_s} \leq 1$$

$$\mathrm{QCE} = \frac{\lambda_s}{\lambda_p} \mathrm{PCE}$$

EDFA

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

we also see that in order to achieve a specific maximum gain G, the input signal power cannot exceed a value given by

$$P_{s,\mathrm{in}} \le \frac{(\lambda_p/\lambda_s) P_{p,\mathrm{in}}}{G-1}$$

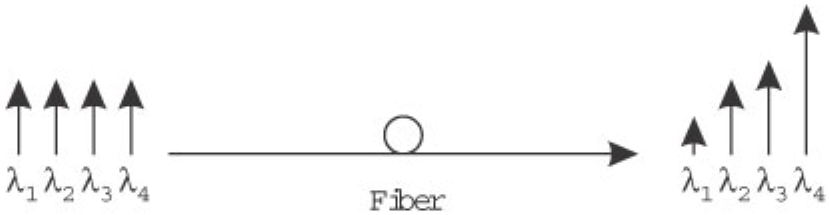
Raman Amplifiers

• Power transferred from lower-l to higher-l channels (about
100nm)
• Eg: 1460-1480nm pump → amplification at 1550-1600nm
• Gain can be provided at ANY wavelength (all you need is an
appropriate
pump l!)
• Multiple pumps can be used

Lumped or distributed designs possible

• Used today to complement EDFAs in ultra-long-haul systems

Raman Amplifier



Raman Amplifier