Lecture 6

Optical Amplifiers

ECE 325

OPTOELECTRONICS

Reading: Kasap – 4.3

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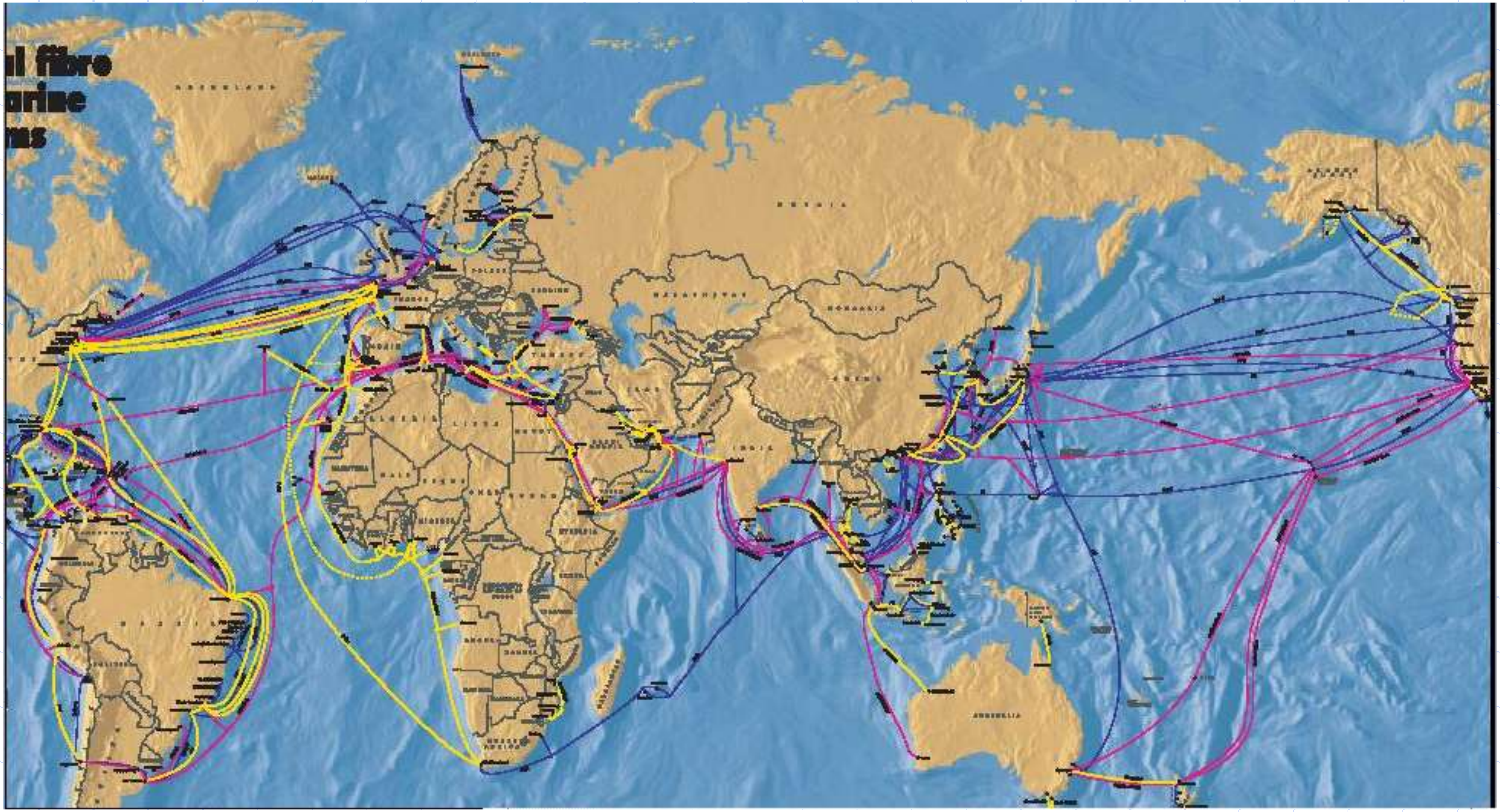
Ahmed Farghal, Ph.D.

Electronics and Electrical Communications Engineering Department

Menoufia University

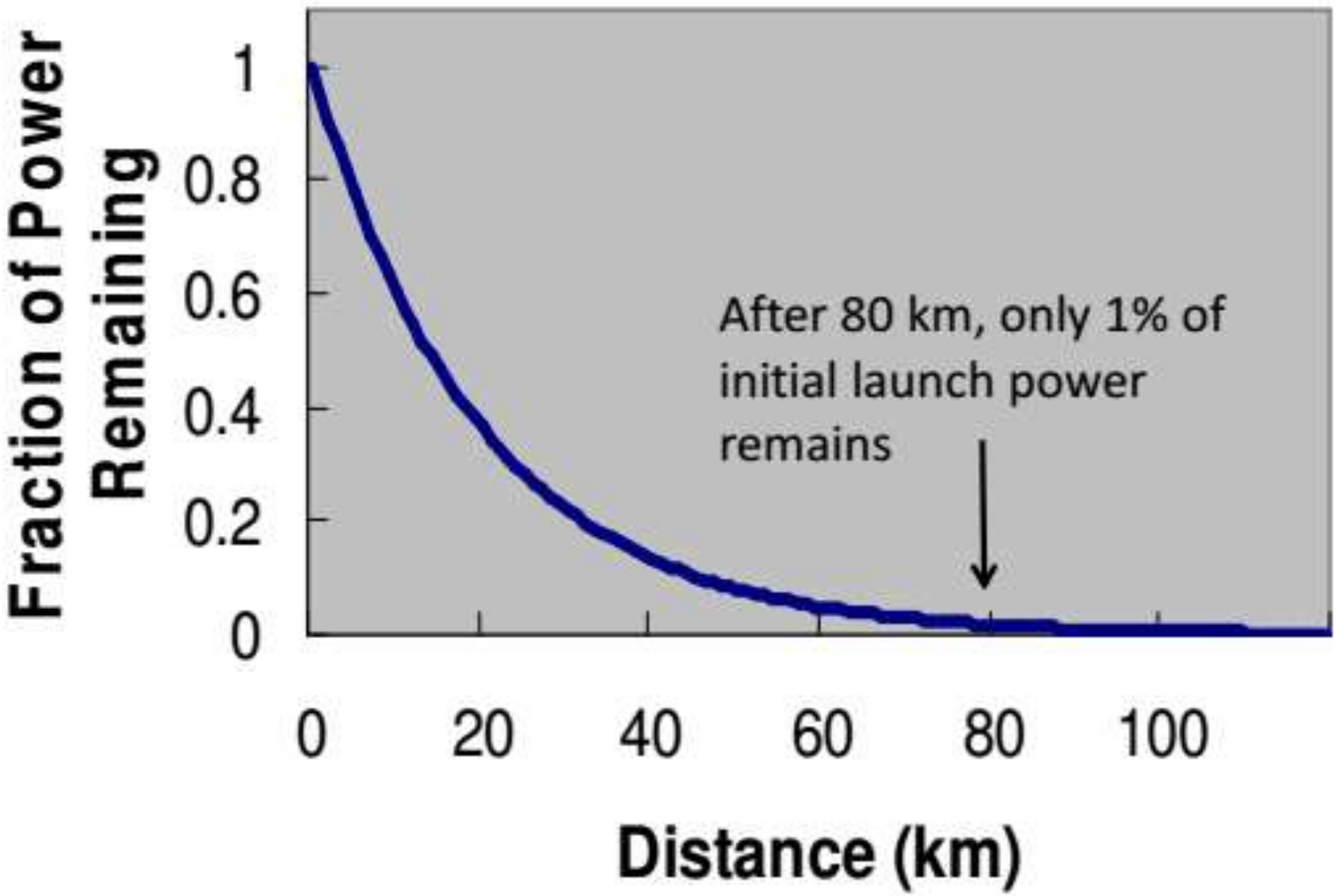
Global telecommunications relies on optical fiber.



Although optical fiber is an excellent transmission medium (lower loss and larger bandwidth compared to coaxial cable, for example), it is not perfect.

Impact of attenuation

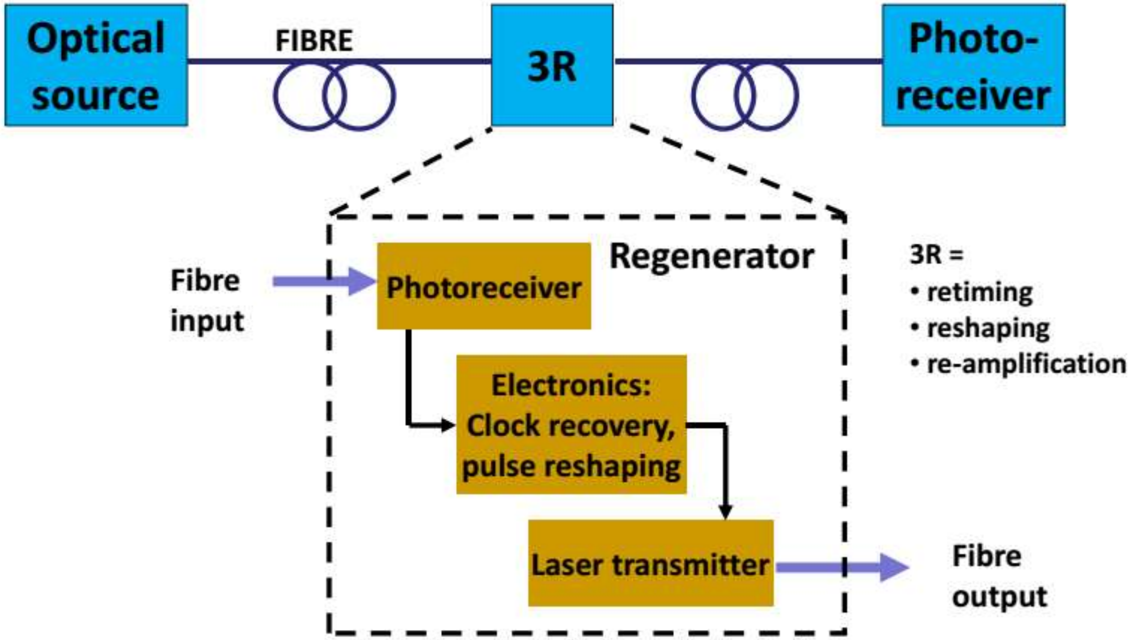
- Consider a fiber with an attenuation factor of 0.25 dB/km:



- A light signal that is traveling along an optical fiber over a long distance suffers marked attenuation.

Optical Signal Regeneration

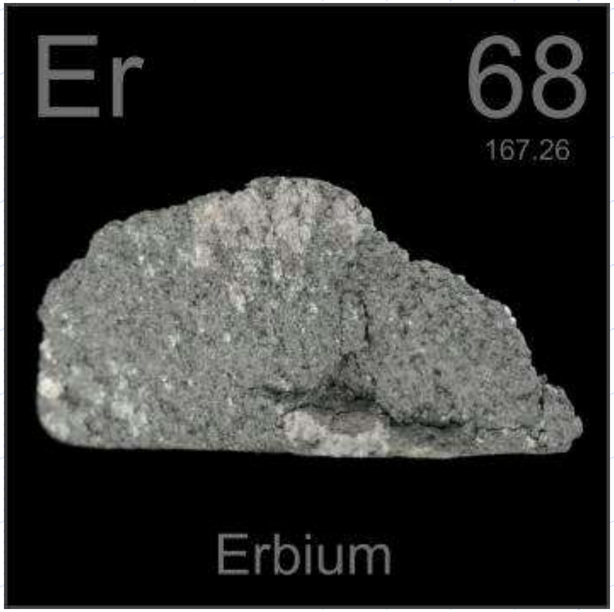
- It becomes necessary to regenerate the light signal at regular intervals for long-haul communications over several thousand kilometers.
  - Regenerate signal by Optical-Electrical-Optical.



- Advantages:
  - Clock recovery
  - Pulse reshaping
- Disadvantages:
  - O/E & E/O conversion needed
  - Bit rate is "locked in" – no upgrades
  - Single wavelength only

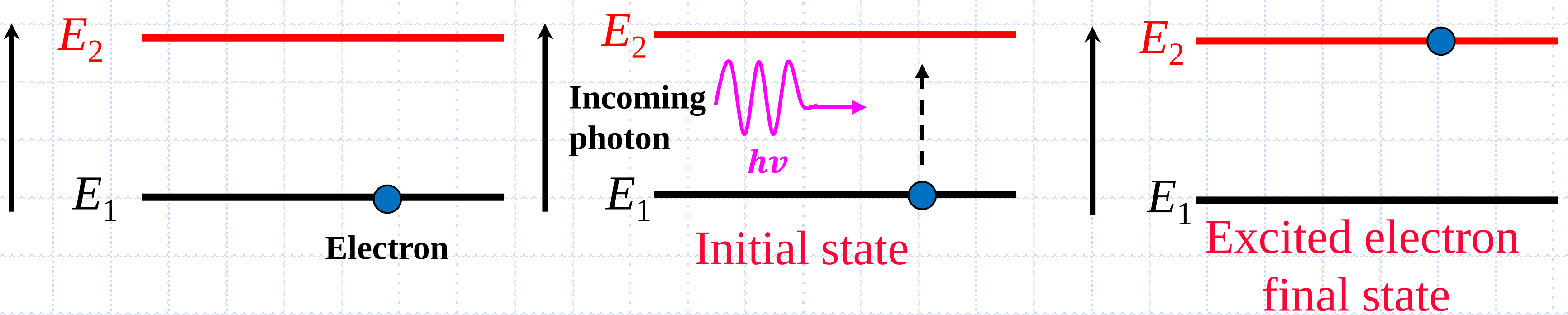
Optical Amplification

- Instead of regenerating the optical signal by photodetection, conversion to an electrical signal, amplification, and then conversion back from electrical to light energy by a laser diode, it becomes practical to amplify the signal directly by using an optical amplifier.
  - Amplify optical signal directly => **optical amplifier**
- One practical optical amplifier is based on the **erbium (Er^{3+} ion)-doped fiber amplifier (EDFA)**.



Absorption

- An electron in an atom can be excited from an energy level E_1 (ground state) to a higher energy level E_2 by the absorption of a photon of energy $h\nu = E_2 - E_1$.
- The energy now acquired by the electron is $h\nu = E_2 - E_1$.

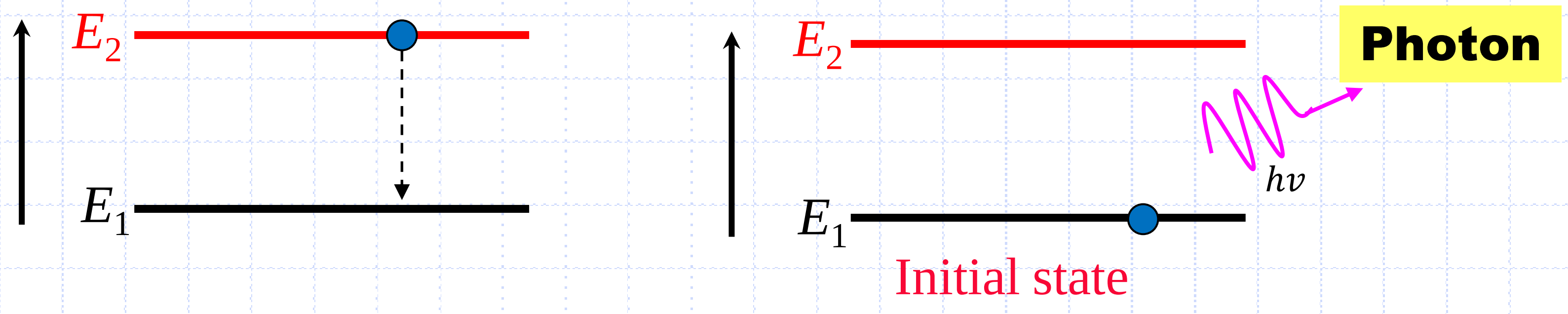


- When an electron at a higher energy level transits down in energy to an unoccupied energy level, it emits a photon.
- There are two possibilities for the emission process:

1. Spontaneous emission, or
2. Stimulated emission.

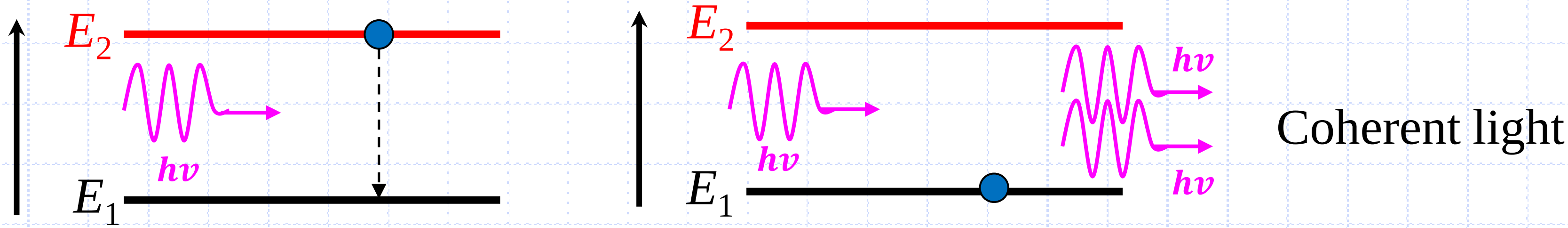
Spontaneous Emission

- In spontaneous emission, the electron can undergo the downward transition from level E_2 to E_1 by itself quite spontaneously.
- The emitted photon has:
  - energy $hv = E_2 - E_1$.
  - a random direction.
- The transition is spontaneous provided that the state with energy E_1 is empty.



Stimulated Emission

- In stimulated emission, an incoming photon of energy $h\nu = E_2 - E_1$ stimulates the whole emission process by inducing the electron at E_2 to transit down to E_1.
- The two photons are:
  - have the same energy, i.e., $h\nu = E_2 - E_1$
  - are in phase,
  - are in the same direction, and
  - have the same polarization.



- Basis for photon amplification since one incoming photon results in two outgoing photons which are in phase.
- How does one achieve a practical light amplifying device based on this phenomenon?

Population Inversion

- To obtain stimulated emission, the incoming photon should not be absorbed by another atom at E_1.
- We must therefore have the majority of the atoms at the energy level E_2. If this were not the case, the incoming photons would be absorbed by the atoms at E_1.
  - When there are more atoms at E_2 than at E_1, we have what is called a **population inversion**.
- Under normal equilibrium conditions, as a result of Boltzmann statistics, **most of the atoms** would be at E_1, and very few at E_2.
- We therefore need to **excite** the atoms, cause **population inversion**, to obtain stimulated emission.
- Two energy levels is not enough to create population inversion!!
  - Since in the steady state, the incoming photon flux will cause as many upward excitations as downward stimulated emissions.
- We need at least 3 energy levels!!!

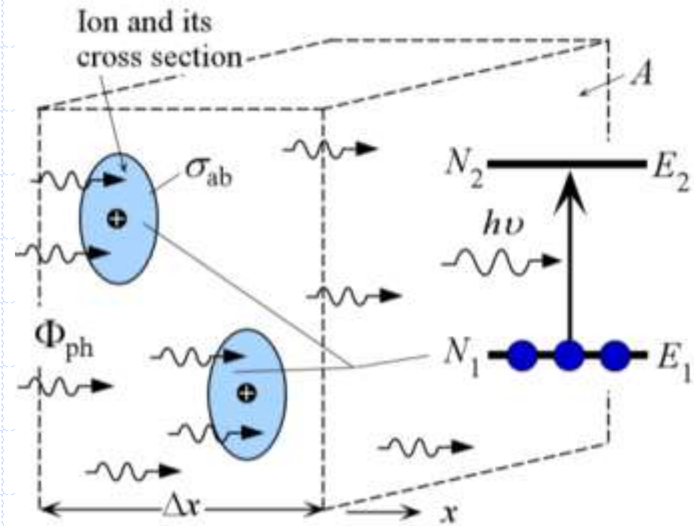
Absorption Cross Section

Total optical power absorbed per unit volume

= Light intensity × Absorption cross section of ion

× Number of ions per unit volume

= $I\sigma_{ab}N_1$



Absorption

- Consider a small volume $A\Delta x$ of the medium, where A is the cross-sectional area and the radiation propagates along x.
- The total optical power ΔP_o absorbed in this volume is then

$$\Delta P_o = (I\sigma_{ab}N_1)(A\Delta x)$$

- Suppose that ΔI is the change (negative if absorption) in the intensity of the propagating radiation over the distance Δx. Then

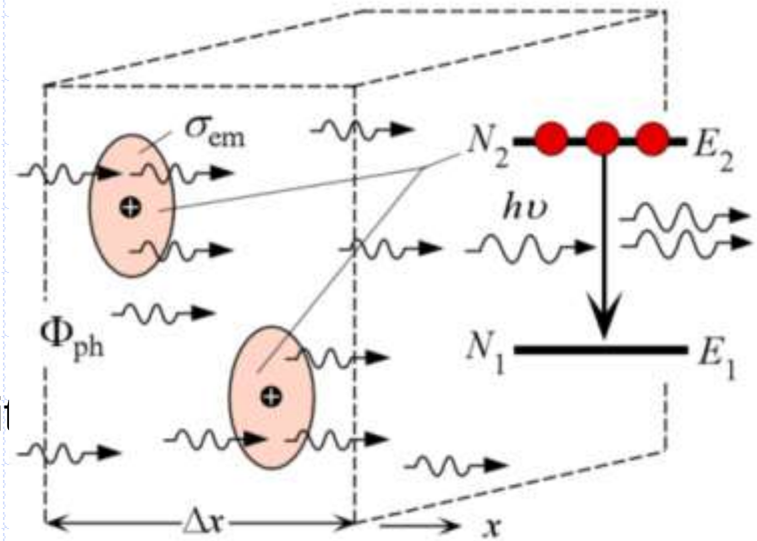
$$A\Delta I = -\text{Total power absorbed in } A\Delta x = -(I\sigma_{ab}N_1)(A\Delta x)$$

$$\boxed{-\frac{\Delta I}{I\Delta x} = \sigma_{ab}N_1 = \alpha}$$

fractional change in the light intensity per unit distance, and therefore represents α, the absorption coefficient of the medium

Emission Cross Section

- The stimulated emission case is similar.
- We can define an **emission cross-section** $\boldsymbol{\sigma_{em}}$ such that if an incident photon crosses the area $\boldsymbol{\sigma_{em}}$, it stimulates the ion to emit a photon as shown in Figure.



Stimulated emission

Stimulated optical power emitted by an ion per unit volume

= Light intensity × Emission cross section of ion

× Number of ions per unit volume

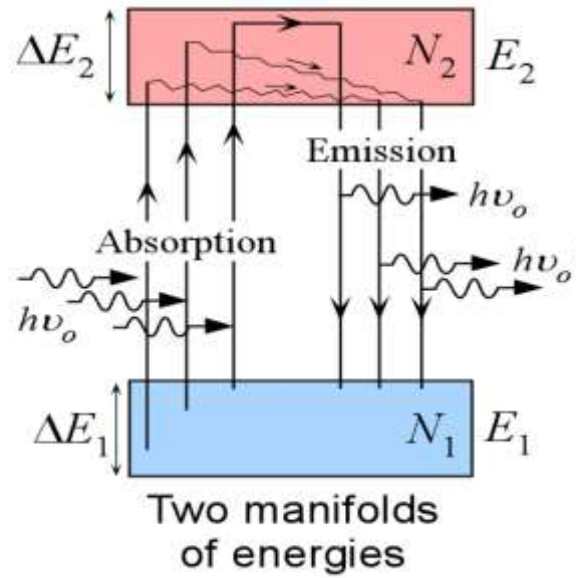
$$= I\sigma_{em}N_2$$

- As the radiation propagates along x, its intensity I increases due to stimulated emissions from E_2 to E_1.
- Since only ions at E_2 with a concentration N_2 can be stimulated to emit, the fractional increase in the intensity per unit distance is

$$\frac{\Delta I}{I\Delta x} = \sigma_{em} N_2$$

Optical Gain Coefficient

- **Gain coefficient *g* of the medium:** the net fractional increase in the intensity I per unit distance, so that, in the presence of stimulated emission and absorption



Definition $$g = \left[\frac{\Delta I}{I\Delta x}\right]_{\text{net}}$$

$$g = \sigma_{em} N_2 - \sigma_{ab} N_1$$

- For manifolds energy levels, we can consider other photon energies besides $h\upsilon_o$, and hence consider σ_{ab} and σ_{em} at other frequencies (wavelengths).

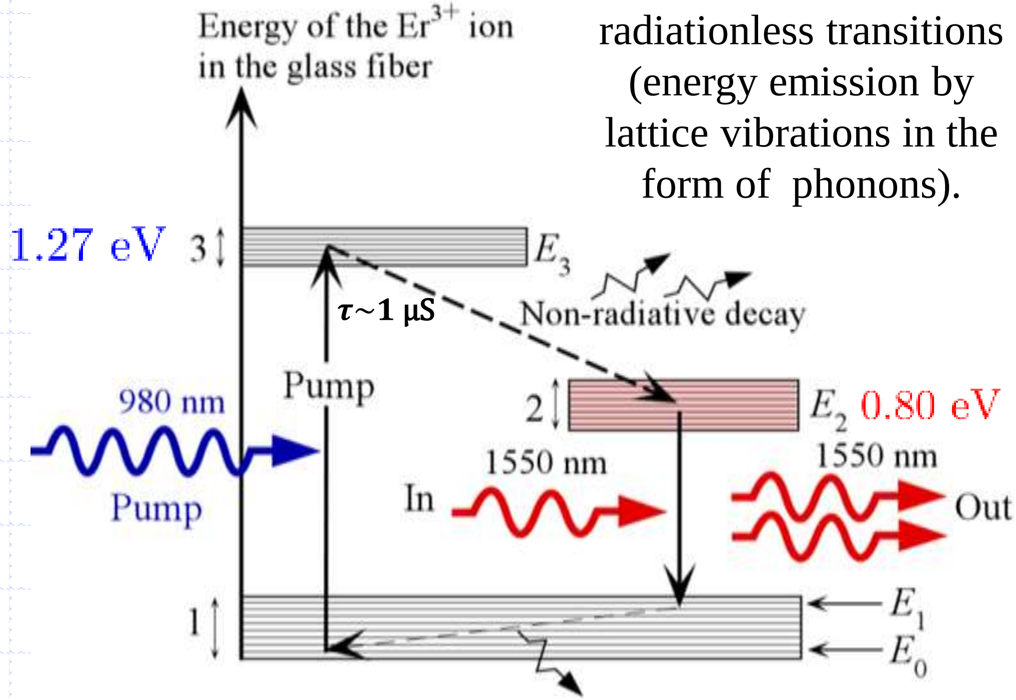
$$g(\lambda) = \sigma_{em}(\lambda) N_2 - \sigma_{ab}(\lambda) N_1$$

Optical gain is $$G = \exp(gL)$$

Light Amplification by Er^{3+} ion in the Glass Fiber

Dashed arrows indicate radiationless transitions (energy emission by lattice vibrations in the form of phonons).

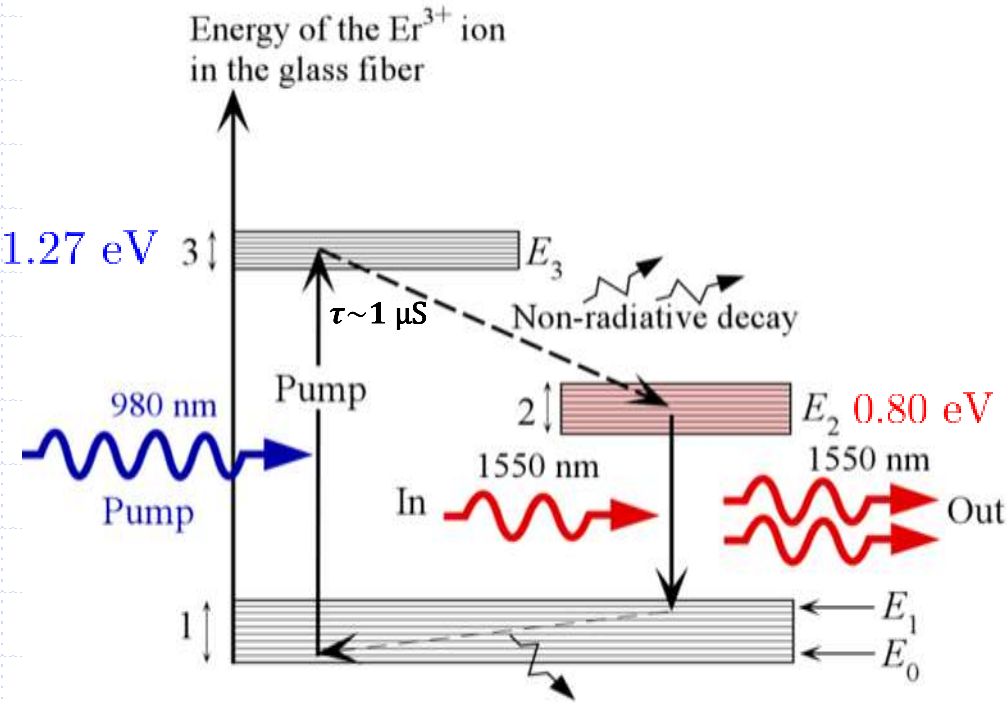
- A common type of an optical amplifier is an erbium ion **(Er^{+3})** doped fiber amplifier (EDFA)
- Er^{3+} ion implanted in the host glass material is a 3-level system (actually mimics a pseudo 4-level system).
- Medium causes **Stark Effect:** energy levels become bands due to doped (not pure) material.



- Thus, the energies of the Er^{3+} ion in the glass actually fall into manifolds of energy levels, which are shown as 1, 2, and 3.
- The Er^{3+} ions are optically pumped, usually from a laser diode, to excite them from the ground energy manifold 1 to 3.
  - The wavelength for this pumping is about 980 nm.

Light Amplification by Er^{3+} ion in the Glass Fiber

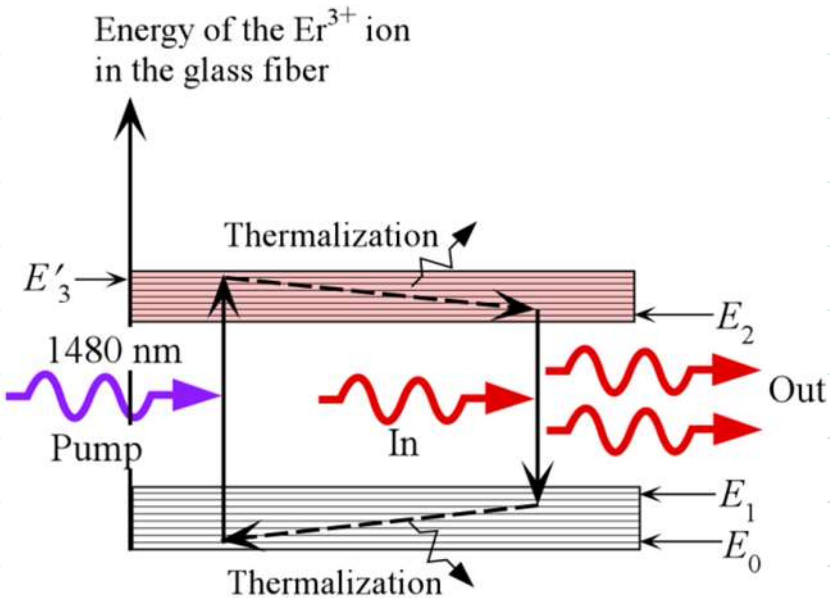
- The Er^{3+} ions then rapidly (~ 1 μs) and nonradiatively decay (by the emission of phonons) from E_3 to a long-lived (~ 10 ms) energy level E_2.
- Thus, more and more Er^{3+} ions accumulate at E_2 ⟹ leads to a population inversion between E_2 and E_1.



- Signal photons around 1550 nm have an energy of 0.80 eV, or $E_2 - E_1$, and give rise to stimulated transitions of Er^{3+} ions from E_2 to E_1.
- Without pumping, Er^{3+} ions at E_1 that will absorb the incoming 1550 nm photons and reach E_2.
- To achieve light amplification we must therefore have stimulated emission exceeding absorption. This is only possible if there are more Er^{3+} ions at E_2 than at E_1; i.e., population inversion.

Light Amplification by Er^{3+} ion in the Glass Fiber

- It is also possible to pump the Er^{3+} ions to the top of the manifold 2.
- The top of manifold 2 now acts like a E_3-level, and is labeled E_3'.
- The pump wavelength is 1480 nm.



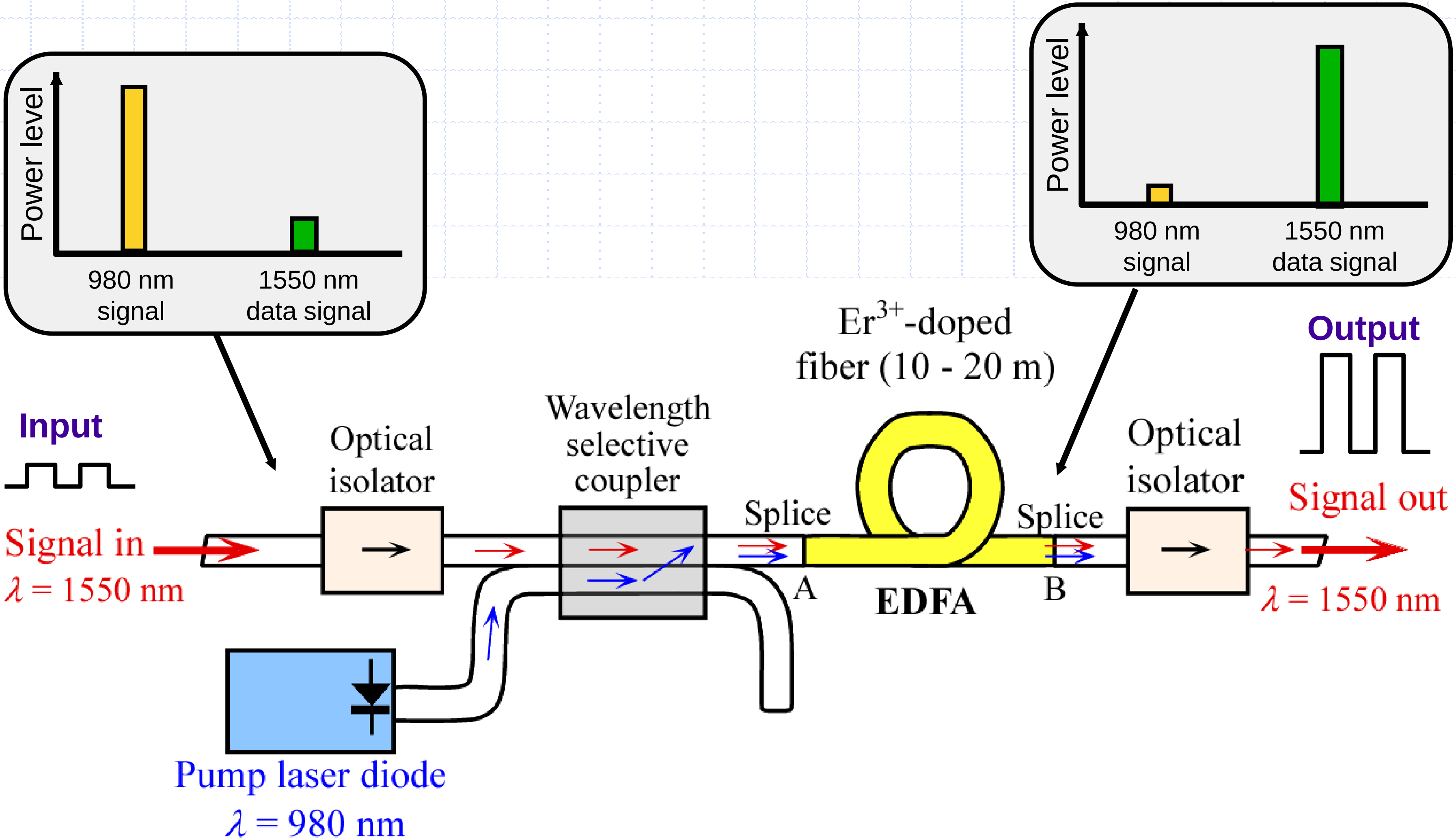
- The Er^{3+} ions decays rapidly by emitting phonons to E_2, and then by stimulated emission down to E_1.
- Pumping at 980 nm is more efficient than pumping at 1480 nm.
  - since it produces less noise and achieves larger population inversions than pumping at 1480 nm

Erbium Doped Fiber Amplifier

EDFA (Strand Mounted Optical Amplifier, Prisma 1550) for optical amplification at 1550 nm. This model can be used underground to extend the reach of networks; and operates over -40 °C to +65 °C. The output can be as high as 24 dBm (Courtesy of Cisco).

EDFAs (LambdaDriver®-Optical Amplifier Modules) with low noise figure and flat gain (to within ±1 dB) for use in DWDM over 1528 - 1563 nm. These amplifiers can be used for booster, in-line and preamplifier applications. (Courtesy of MRV Communications, Inc)

Erbium Doped Fiber Amplifier



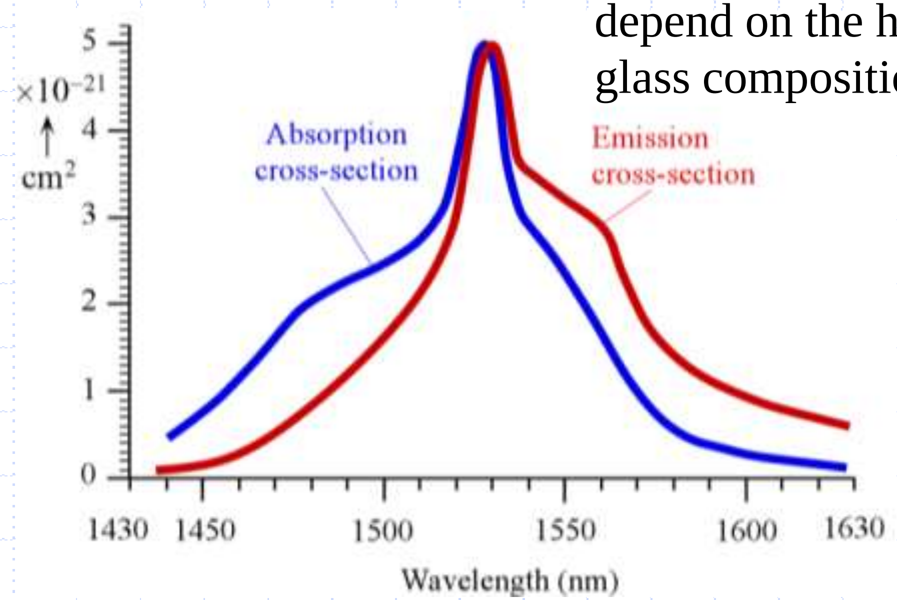
A simplified schematic illustration of an EDFA (optical amplifier). The erbium-ion doped fiber is pumped by feeding the light from a laser pump diode, through a coupler, into the erbium ion doped fiber

Erbium Doped Fiber Amplifier

- **Erbium (Er^{3+} ion)-doped fiber amplifier (EDFA)**.
  - The core region of an optical fiber is doped with Er^{3+} ions.
  - The host fiber core material is a glass based on silica-aluminate (SiO_3-Al_2O_3) or silica-germania (SiO_3-GeO_2), or both.
  - It is fused to a single-mode long-distance optical fiber by splicing.
- It is pumped from a laser diode through a coupling fiber arrangement which allows only the pumping wavelength to be coupled; it is a **wavelength-selective coupler**.
- **Optical isolators** at the entry and exit end of the amplifier:
  - allow only the optical signals at 1550 nm to pass in one direction
  - prevent the 980 pump light from propagating back or forward into the communication system.
- A photodetector system coupled to monitor the pump power or the EDFA output power (not shown).

Erbium Doped Fiber Amplifier

Typical absorption and emission cross sections, σ_{ab} and σ_{em} respectively, for Er^{3+} in a silica glass fiber doped with alumina (SiO_2-Al_2O_3).



depend on the host glass composition

$$g(\lambda) = \sigma_{em}(\lambda)N_2 - \sigma_{ab}(\lambda)N_1$$

- Under strong pumping, $N_2 \gg N_1$:

$$g(\lambda) \approx \sigma_{em}(\lambda)N_2 \approx \sigma_{em}(\lambda)N_0$$

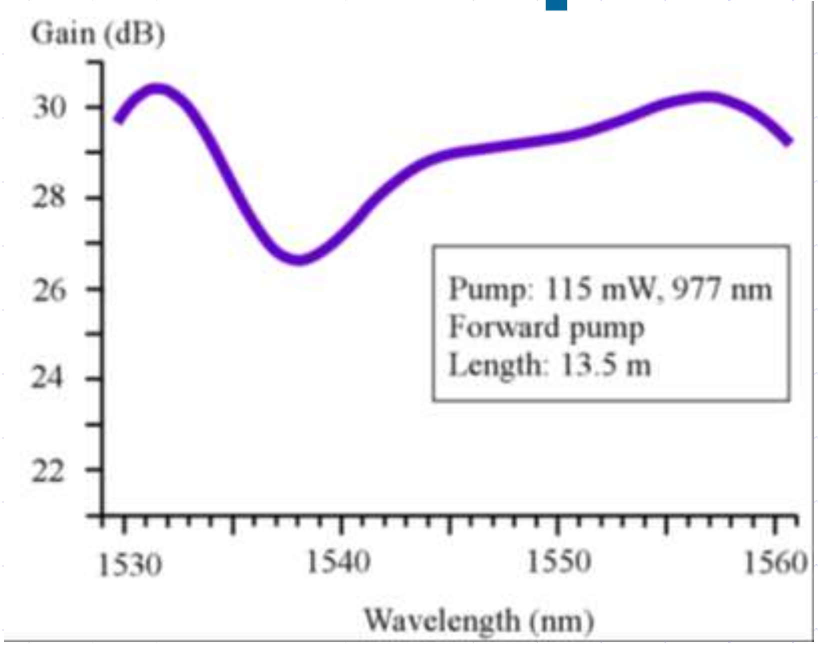
  - where N_0 is the Er^{3+} concentration in the core of the fiber.

- The absolute maximum gain with nearly full inversion would be

$$G = \exp(\sigma_{em}N_0L)$$

Thus, σ_{em} vs. λ also represents the spectral dependence of the gain coefficient under strong pumping.

EDFA Gain Spectrum

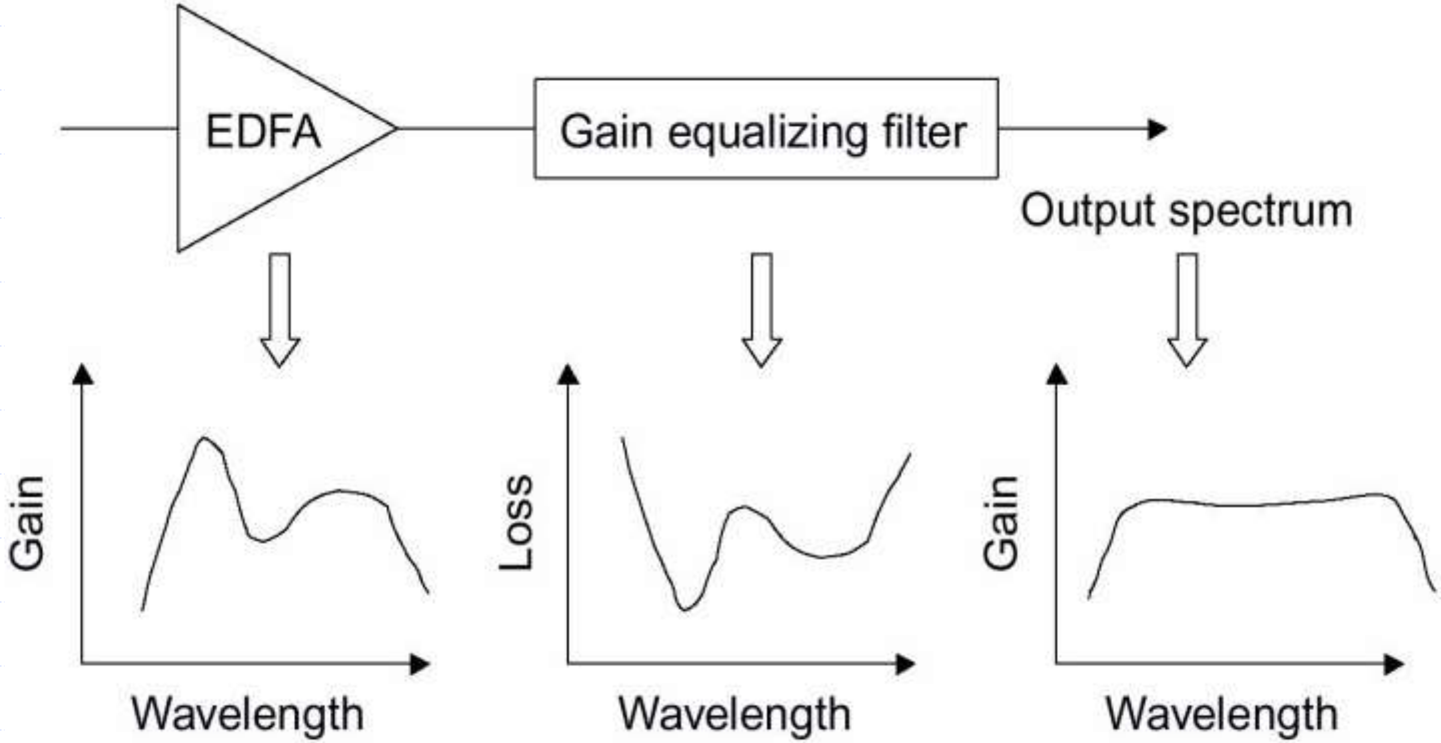


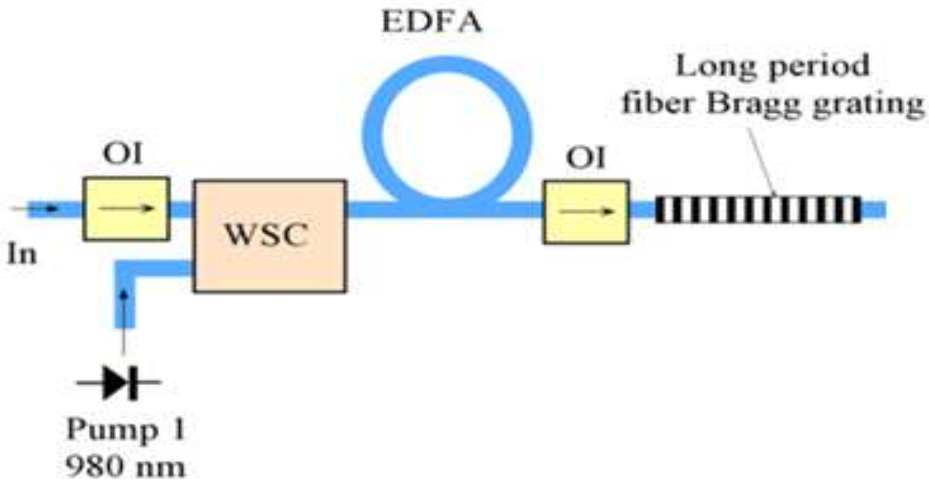
$$G = \exp(\sigma_{em} N_0 L)$$

The spectral characteristics of gain, G in dB, for a typical commercial EDF, available from Fibercore as IsoGain™ fiber. Forward pumped at 115 mW and at 977 nm.

- High gain over a wide spectral bandwidth.
- The gain spectrum is not "flat"; there is a peak around 1530 nm.
- The gain is normally flattened to obtain uniform gain over the band of wavelengths used in multi channel communications.

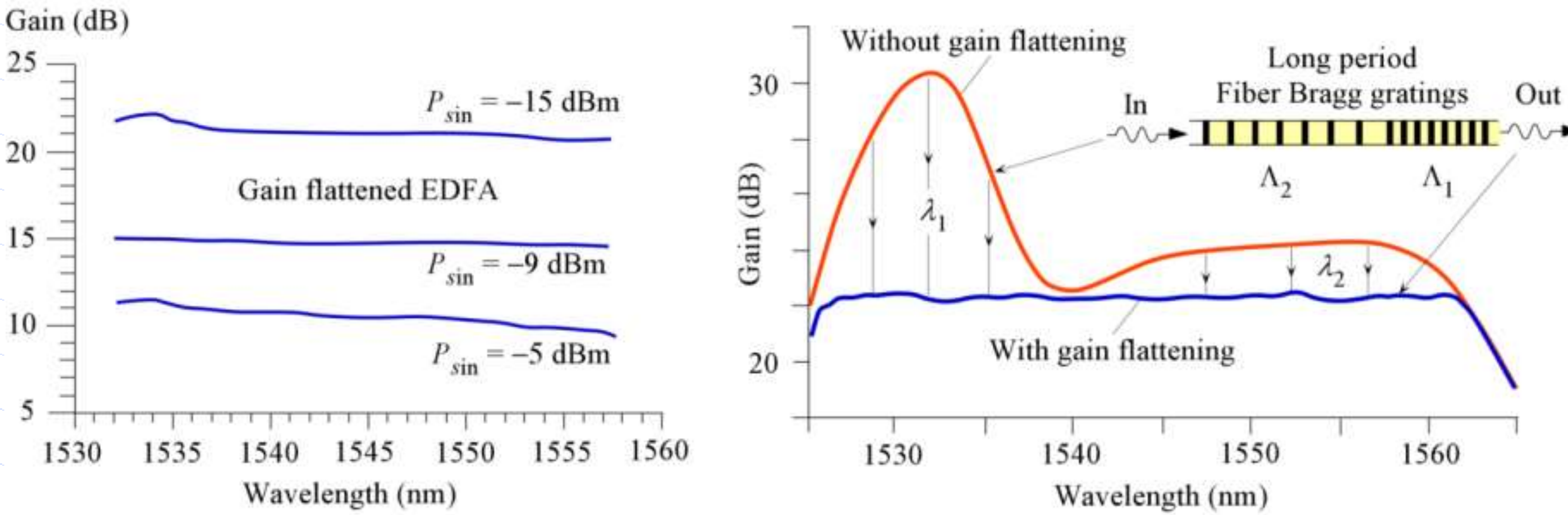
EDFA Gain-Flattening





EDFA Gain-Flattening

(a) (b)

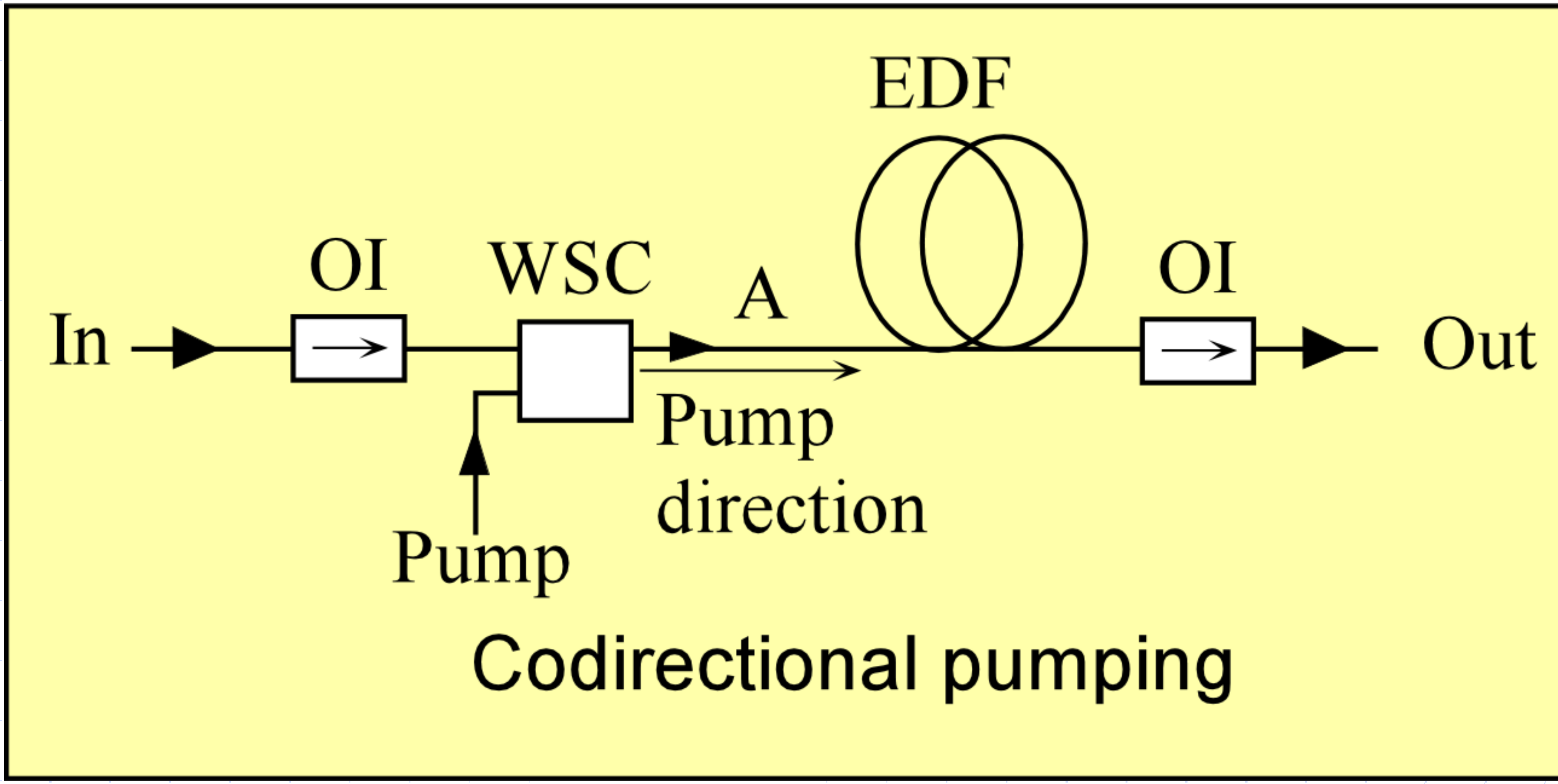


(a) The gain spectrum of one type of commercial gain flattened EDFA. The gain variation is very small over the spectrum, but the gain decreases as the input power increases due to saturation effects (Note, the corresponding power levels are 0.031, 0.13 and 0.32 mW).

(b) Schematic illustration of gain equalization by using long fiber Bragg grating filters in series that attenuate the high gain regions to equalize the gain over the spectrum. (An idealized example.)

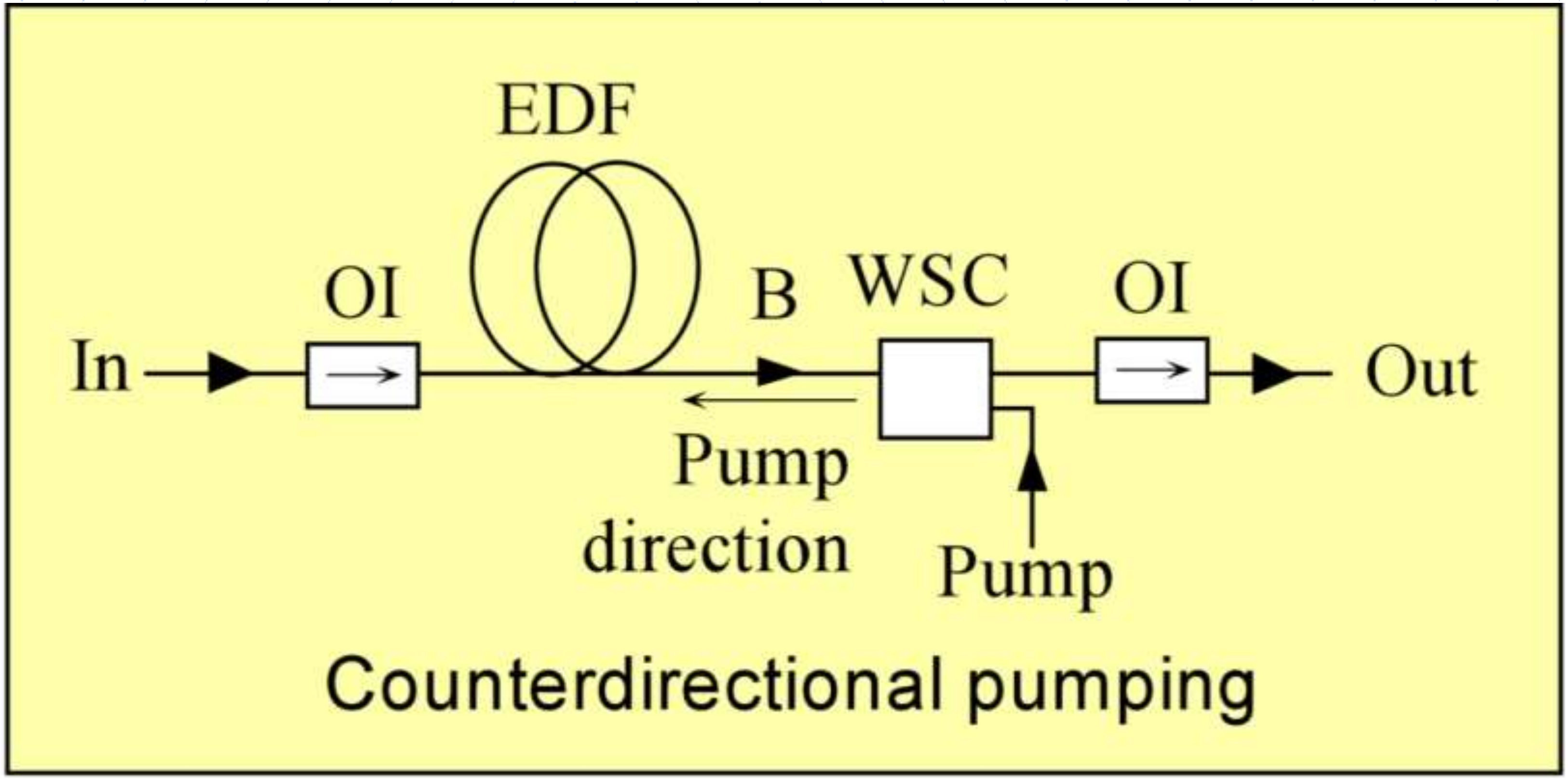
EDFA Configurations

Codirectional/Forward Pumping



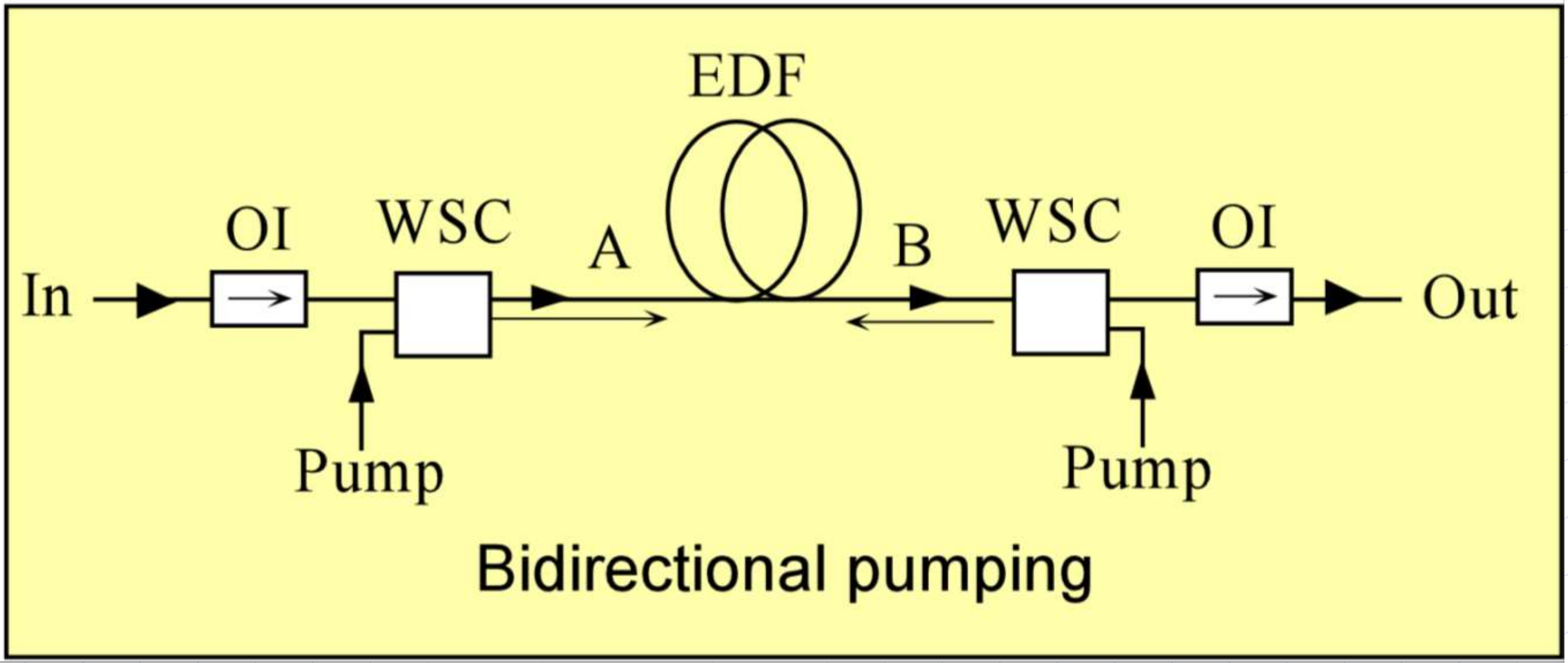
- The pump light is feed at A.
- The pump light and the signal travel in the same direction.
- lower noise but lower output power

Counterdirectional/backward pumping



- The pump light is feed at B, in which the pump light propagates in the opposite direction to the signal.
- higher output power but higher noise

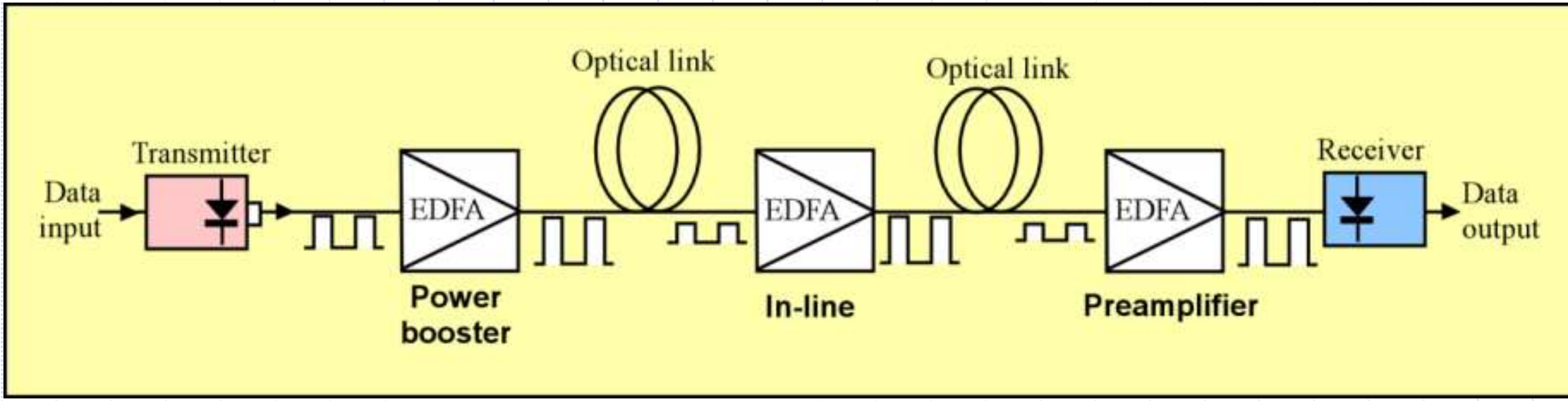
Bidirectional/Dual Pumping

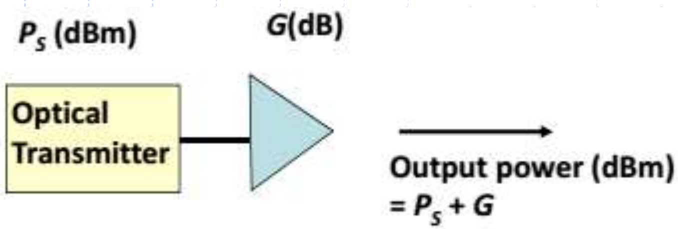


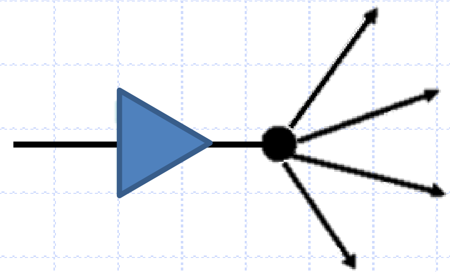
- In bidirectional pumping, also called dual pumping, there are two pump diodes coupled to the EDF at A and B as shown in the figure.
- Population inversion relatively uniform along amplifier length.

EDFA Applications

Power Booster

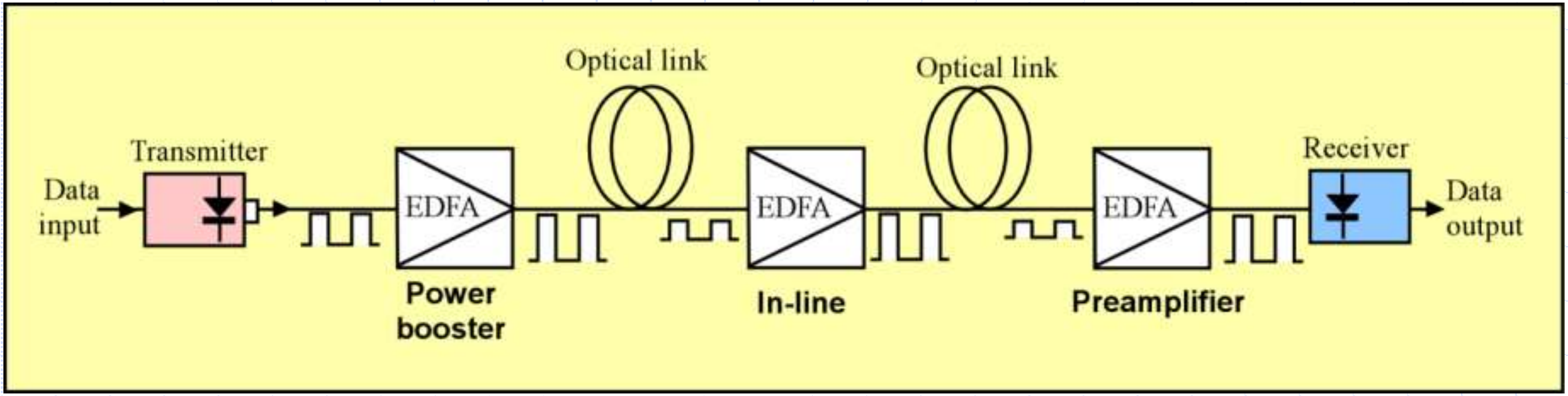




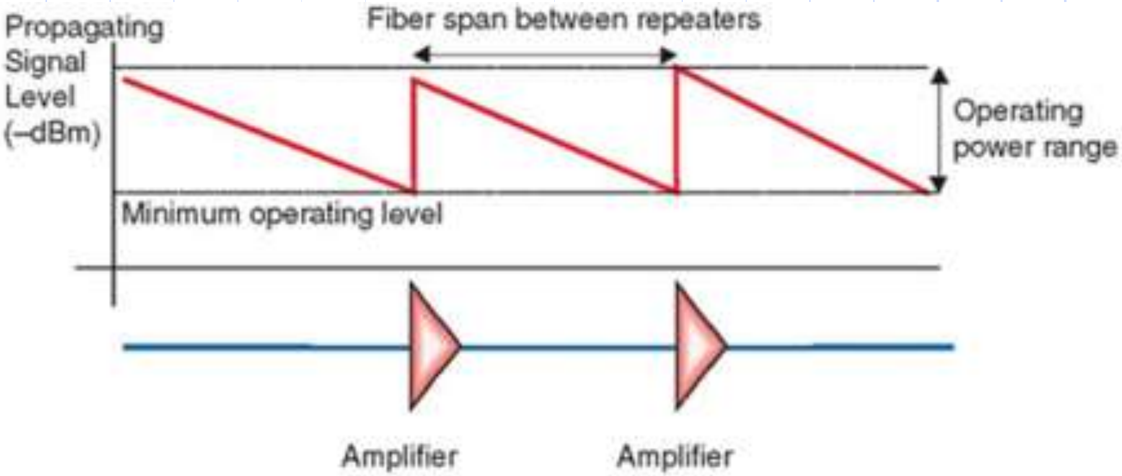


- The EDFA is placed after the transmitter to boost the signal power fed into the optical network.
- Quite often the signal from a transmitter needs to be boosted if the signal is to be split into N channels through an optical splitter.
- Booster EDFAs are designed so that the output signal does not easily saturate for large input signals.

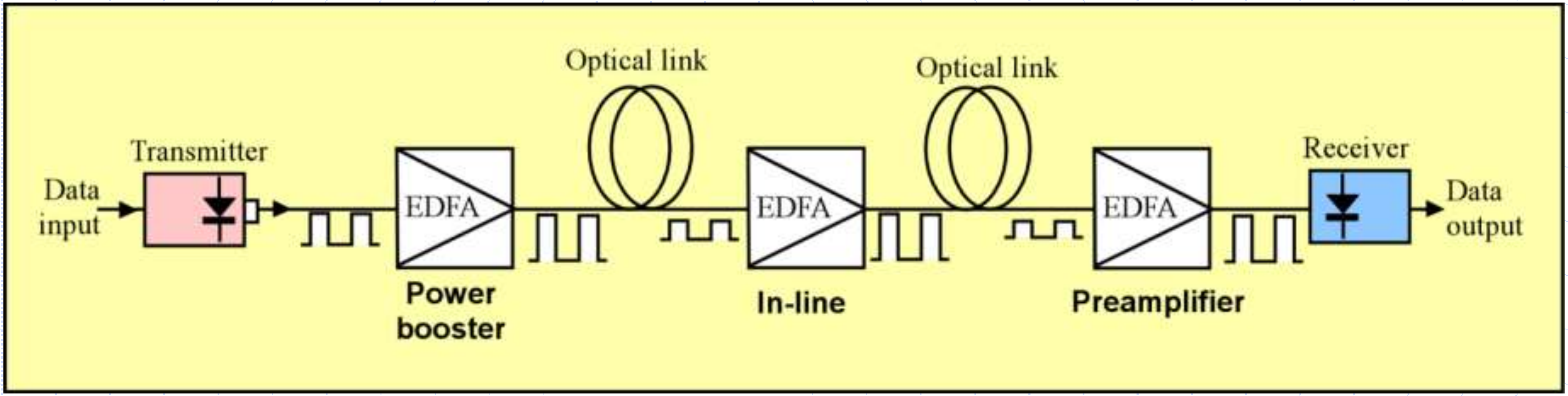
In-line Amplifier



- The EDFA is placed within the optical transmission link, where the signal has become weak and needs to be amplified.
- The in-line EDFA should have a large gain and add very little noise into the fiber.



Preamplifier

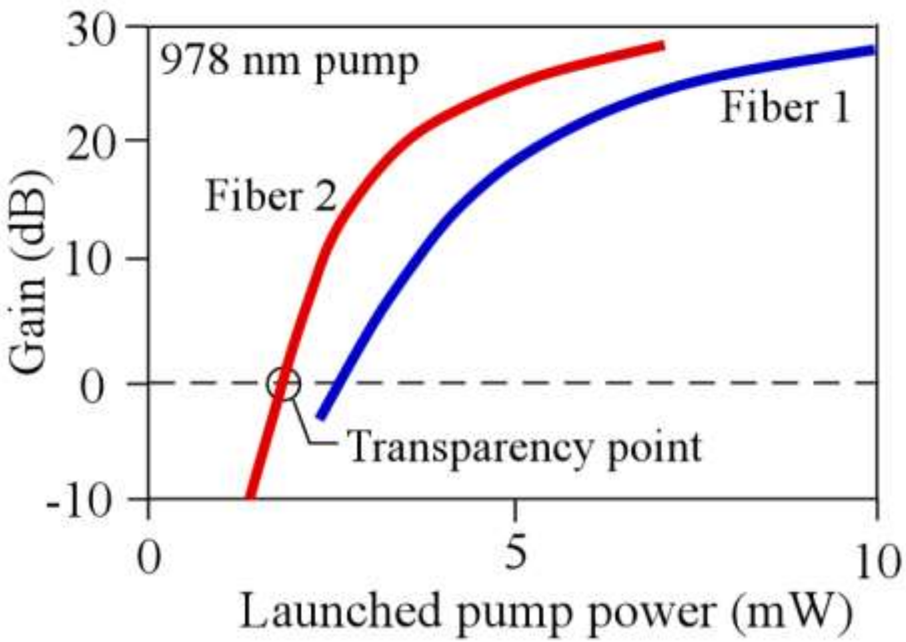


- Optical amplifier is placed immediately before the optical receiver in order to improve sensitivity.
- At this point the signal is weak, so good gain is required, but even more important is the fact that the amplifier must not add a lot of noise, so a low noise figure is required (typically less than 5 dB).

EDFA Gain vs Launched Pump Power

Typical characteristics of EDFA small signal gain in dB vs launched pump power for two different types of fibers pumped at 980 nm. The fibers have different core compositions and core diameter, and different lengths (L_1 = 19.9 m, and L_2 = 13.6 m)

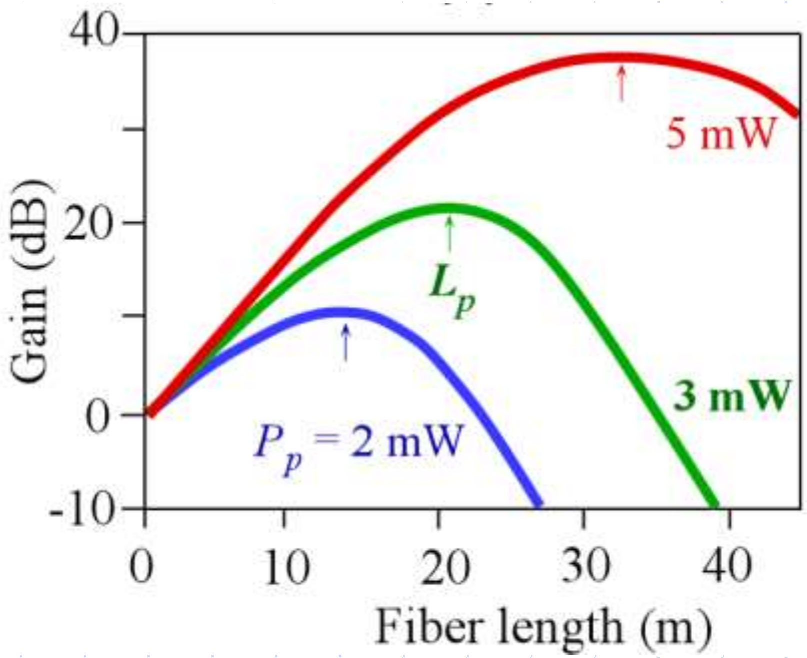
$$g = \sigma_{em} N_2 - \sigma_{ab} N_1$$



- As more pump power is fed into the core of the EDFA, N_2 increases and N_1 decreases given that $N_1 + N_2 = N_0$, the Er^{3+} concentration in the fiber.
  - The gain of an EDFA depends on the launched pump power from the pump diode.
- From the figure, as expected, G first increases sharply with P_p.
- At high pump powers, further increases in N_2 and hence G become constrained due to the diminishing population N_1 with increasing pump power.

Gain as a function of length of EDF

$G = \exp(gL)$



- Initially G increases with L but then drops with L for long fiber lengths. i.e., there is an optimum fiber length or pump length that maximizes the gain at a given launched pump power.
- Beyond this optimum length, the pump power in the core decreases with length so much that the gain disappears and the fiber attenuates the signal, which is highly undesirable.
- Thus, it is important to design the EDFA with a length that is not longer than the optimum length.
- The optimum fiber length is longer for higher launched pump powers.

EDFA Pump Length

- The absorbed pump power is primarily taken by those excited ions that have spontaneously decayed from E_2 to E_1, because these have to be pumped back up to E_3 and hence E_2.

$$\begin{aligned}\text{Absorbed pump power} = & \text{ Absorbed energy per unit time} \\ & \approx (\text{Volume})(N_2)(\text{Pump photon energy})/(\text{Decay time}) \\ & = (AL_p)(N_2)(h\nu_p)/\tau_{sp}\end{aligned}$$

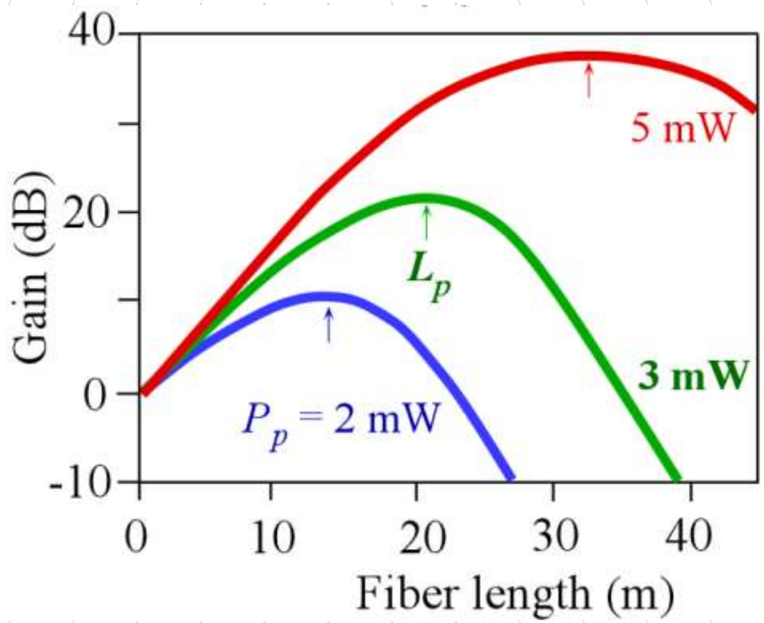
A is the cross-sectional area of the fiber core that has the Er^{3+} dopants, and L_p is the length of fiber needed to absorb the necessary pump radiation, ν_p is the pump frequency, τ_{sp} spontaneous emission lifetime.

- Under strong pumping, i.e., $N_2 \approx N_0$, the absorbed pump power P_p:

$$P_p \approx AN_0 h\upsilon_p L_p/\tau_{\text{sp}}$$

This equation essentially determines the maximum fiber length allowed for a given amount of pumping.

EDFA Pump Length



$$g = \sigma_{em} N_2 - \sigma_{ab} N_1$$

$$G = \exp(gL)$$

$$P_p \approx A N_0 h \upsilon_p L_p / \tau_{sp}$$

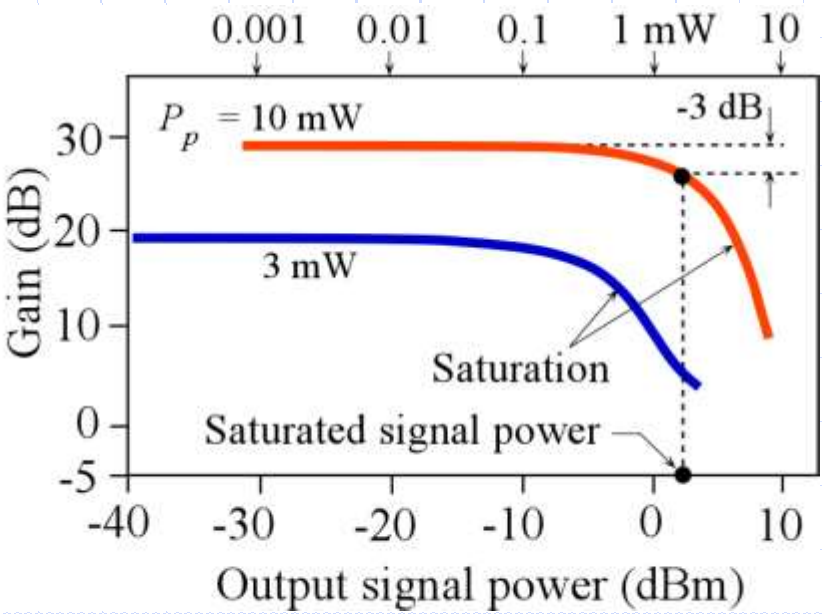
- Not all the pump radiation will be confined to the fiber core. Only some fraction Γ (0.6–0.8), called the confinement factor, of the pump radiation will be guided within the core and hence pump the Er^{3+} ions.

Confinement factor

$$\Gamma P_p \approx A N h \upsilon_p L_p / \tau_{sp}$$

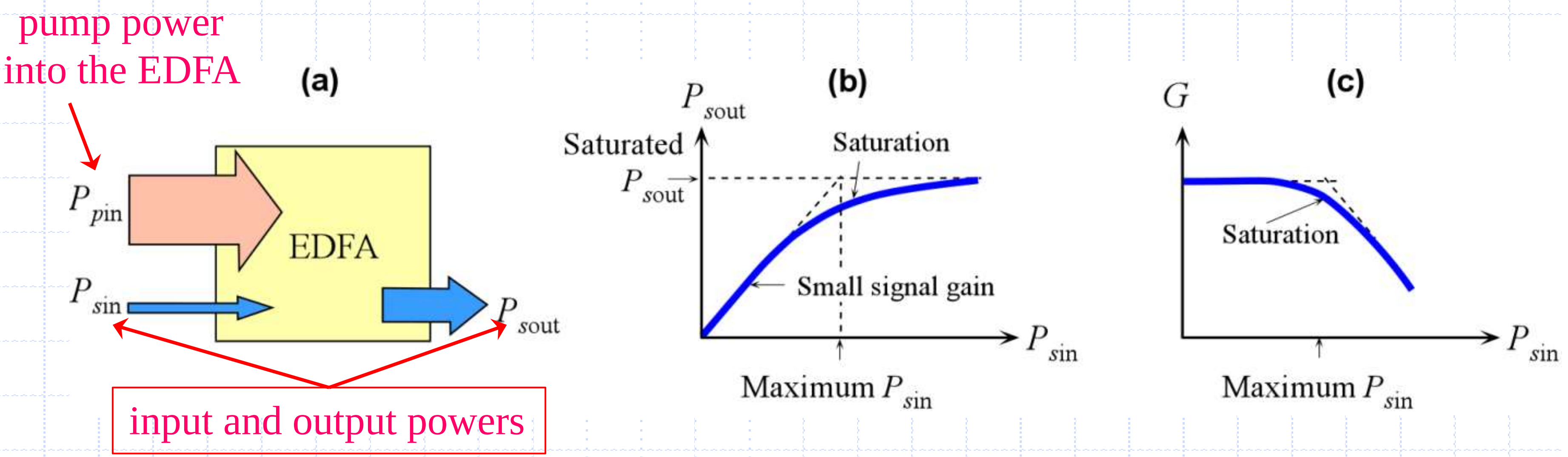
EDFA Gain Saturation

Typical dependence of gain on the output signal strength for different launched pump powers. At high output powers, the output signal saturates, *i.e.* the gain drops.



- One very important characteristic of an EDFA is the saturation of its output signal power, that is, the fall in the gain, under large signals.
- As the signal is amplified, the optical power at 1550 nm in the fiber core increases, which itself encourages further stimulated emission and thereby depopulates the population N_2; and hence the gain drops.
- **The saturated output power**, (the power at which gain saturation occurs) is defined as the output signal at which the gain drops by 3 dB below its constant small signal value.
- It is simply called the maximum output power and is quoted in dBm.

EDFA Power-Conversion Efficiency and Gain



- The power conversion efficiency (PCE), η_{PCE}: represents the efficiency with which the amplifier is able to convert power from the pump to the signal.

$$\eta_{\mathrm{PCE}} = \frac{P_{s,\mathrm{out}} - P_{s,\mathrm{in}}}{P_{p,\mathrm{in}}} \approx \frac{P_{s,\mathrm{out}}}{P_{p,\mathrm{in}}}$$

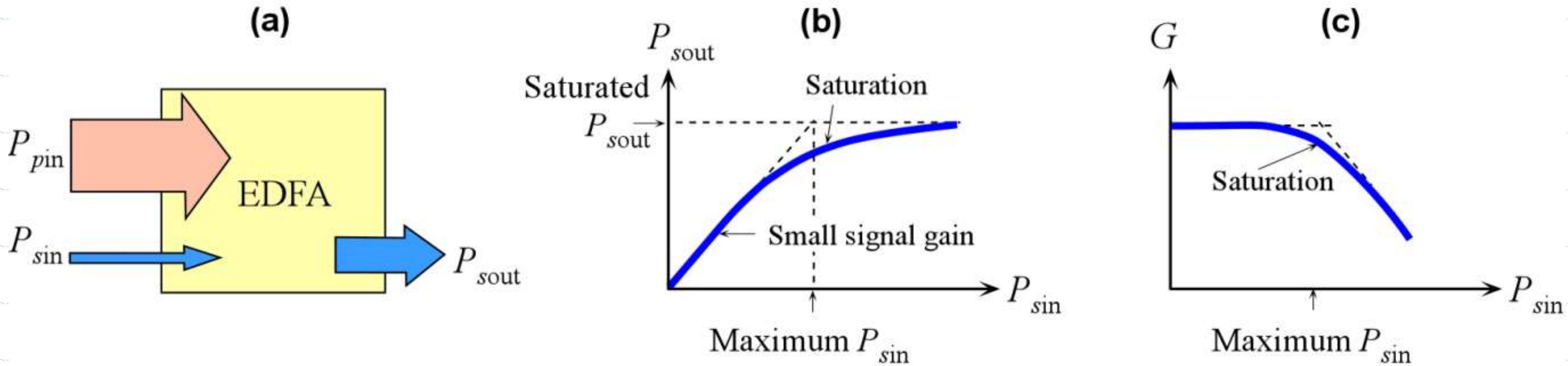
- Suppose that the flux of photons from the pump is $\Phi_{p,\mathrm{in}}$ and the signal input and output photon fluxes are $\Phi_{s,\mathrm{in}}$ and $\Phi_{s,\mathrm{out}}$.
- Since optical power is proportional to photon flux $\times\, hc/\lambda$ where hc/λ is the photon energy, then

$$\eta_{\mathrm{PCE}} \approx \frac{\Phi_{s,\mathrm{out}}}{\Phi_{p,\mathrm{in}}} \times \frac{\lambda_p}{\lambda_s}$$

pump and signal wavelengths

maximum PCE ($= \lambda_p/\lambda_s$) is 63% for 980 nm pumping

EDFA Power-Conversion Efficiency and Gain



- The gain can be defined and written as

$$G = \frac{P_{s,\text{out}}}{P_{s,\text{in}}} = 1 + \eta_{\text{PCE}} \left(\frac{P_{p,\text{in}}}{P_{s,\text{in}}} \right)$$

- The maximum gain $G_{\max}$ is for $\eta_{PCE} = \lambda_p/\lambda_s$ so that $G \leq G_{\max}$ implies

$$G \leq 1 + (\lambda_p/\lambda_s)(P_{p,\text{in}}/P_{s,\text{in}})$$

- Rearranging, the input signal is $P_{s,\text{in}} < (\lambda_p/\lambda_s)P_{p,\text{in}} / (G-1)$

The importance of this equation is that it specifies the range of input signals, that is, the maximum input signal power, beyond which the output signal power begins to saturate as indicated in Figure (b). Consequently, the gain drops with the input signal power as in Figure (c).

This phenomenon is called gain saturation or compression

EXAMPLE: An erbium doped fiber amplifier

Consider a 3 m EDFA that has a core diameter of 5 μm, Er^{3+} doping concentration of 1×10^{19} cm^{-3} and τ_{sp} (the spontaneous decay time from E_2 to E_1) is 10 ms. The fiber is pumped at 980 nm from a laser diode. The pump power coupled into the EDFA fiber is 25 mW. Assuming that the confinement factor Γ is 70%, what is the fiber length that will absorb the pump radiation? Find the small signal gain at 1550 nm for two cases corresponding to full population inversion and 90% inversion.

Solution

The pump photon energy $h\upsilon = hc/\lambda = (6.626\times10^{-34})(3\times10^{8})/(980\times10^{-9}) = 2.03\times10^{-19}$ J (or 1.27 eV)

Rearranging Eq. (4.3.6), we get

$$L_p \approx \Gamma P_p \tau_{sp} / A N h\upsilon_p$$

i.e.

$$L_p \approx (0.70)(25\times10^{-3}\text{ W})(10\times10^{-3}\text{ s}) / [\pi(2.5\times10^{-4}\text{ cm})^2(1\times10^{19}\text{ cm}^{-3})(2.03\times10^{-19}\text{ J})] = \mathbf{4.4\ m}$$

which is the maximum allowed length. The small signal gain can be rewritten as

$$g = \sigma_{em}N_2 - \sigma_{ab}N_1 = [\sigma_{em}(N_2/N_0) - \sigma_{ab}(N_1/N_0)]N_0$$

where $N_1 + N_2 = N_0$ is the total Er^{3+} concentration. Let $x = N_2/N_0$, then $1 - x = N_1/N_0$ where x represents the extent of pumping from 0 to 1, 1 being 100%.

Solution (continued)

Thus, the above equation becomes

$$g = [\sigma_{em}x - \sigma_{ab}(1-x)]N_0$$

For 100% pumping, $x = 1$,

$$g = [(3.2\times10^{-21}\text{ cm}^2)(1) - 0](1\times10^{19}\text{ cm}^{-3}) = 3.2\text{ m}^{-1}$$

and

$$G = \exp(gL) = \exp[(3.2\text{ m}^{-1})(3\text{m})] = 14{,}765 \text{ or } \mathbf{41.7\ dB}$$

For $x = 0.9$ (90% pumping), we have

$$g = [(3.2\times10^{-21}\text{ cm}^2)(0.9) - (2.4\times10^{-21}\text{ cm}^2)(0.1)](1\times10^{19}\text{ cm}^{-3})$$

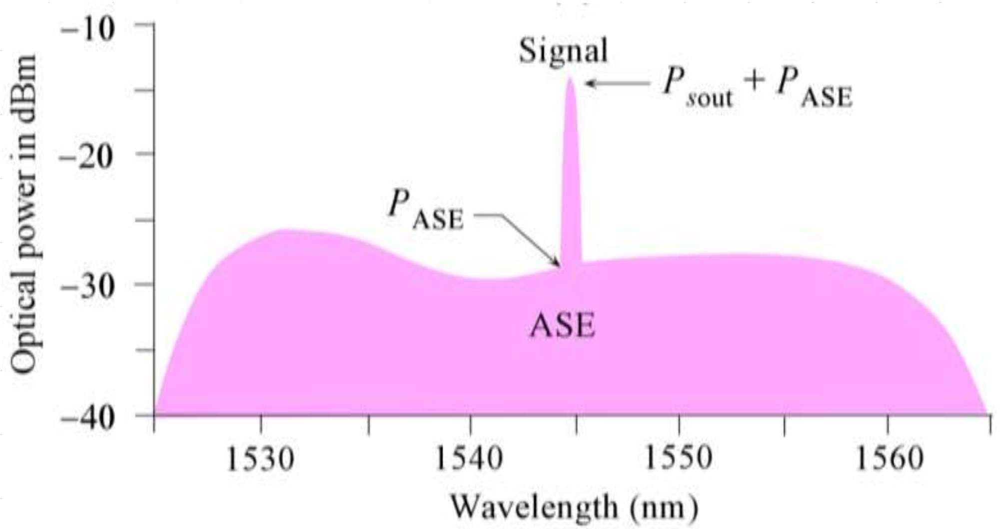
$$= 2.64\text{ m}^{-1}$$

and

$$G = \exp(gL) = \exp[(2.64\text{ m}^{-1})(3\text{m})] = 2{,}751 \text{ or } \mathbf{34.4\ dB}$$

Even at 90% pumping the gain is significantly reduced. At 70% pumping, the gain is 19.8 dB. In actual operation, it is unlikely that 100% population inversion can be achieved; 41.7 dB is a good indicator of the upper ceiling to the gain.

EDFA Noise



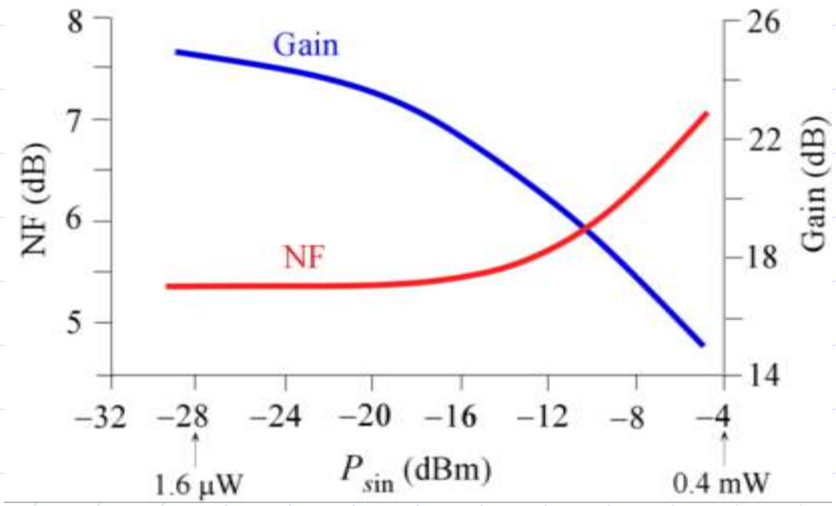
- Like all amplifiers, EDFAs also generate noise in addition to the amplification they provide.
- The noise in an EDFA arises from amplified spontaneous emission (ASE), which is the amplification of randomly emitted photons from the upper E_2-manifold to the lower E_1-manifold.
- This spontaneous emission generates random photons, and as these photos travel along the fiber, they become amplified.
    - Thus, the output from an EDFA not only has the signal but also noise from the ASE as shown in Figure (a).

EDFA Noise

- Noise characteristics of amplifiers are generally quantified by their noise figure (NF), defined by

$$NF = \frac{SNR_{in}}{SNR_{out}}$$

$$NF(dB) = 10\log\left(\frac{SNR_{in}}{SNR_{out}}\right)$$



- For a noiseless amplifier, NF = 0 dB (or 1).
- As shown in the Figure, the NF is initially independent of the input signal power $P_{s,\mathrm{in}}$ level, but at sufficiently high $P_{s,\mathrm{in}}$, it increases with $P_{s,\mathrm{in}}$; or put differently, NF increases with falling gain.

Thank you

Have a nice day.