Optical Fiber Communications

Chapter 11

Optical Amplifiers

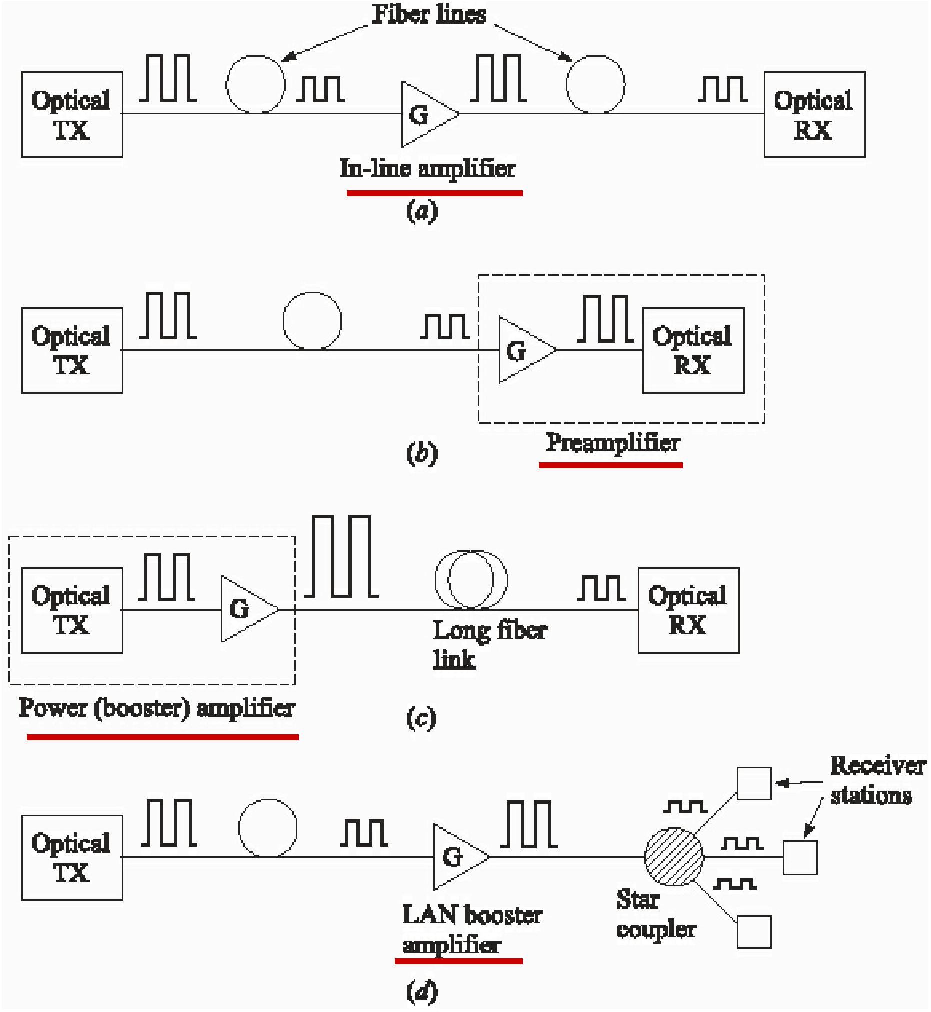
Optical Amplifier Categories

In-Line Amplifier:
Boosts the signal level within a long-distance optical fiber link

Preamplifier:
Boosts the signal to improve the incoming signal-to-noise ratio

Power Amplifier:
Provides "momentum" for transmitted signals at the start of a link

Booster Amplifier:
Compensates for passive coupling and splitting losses in a LAN

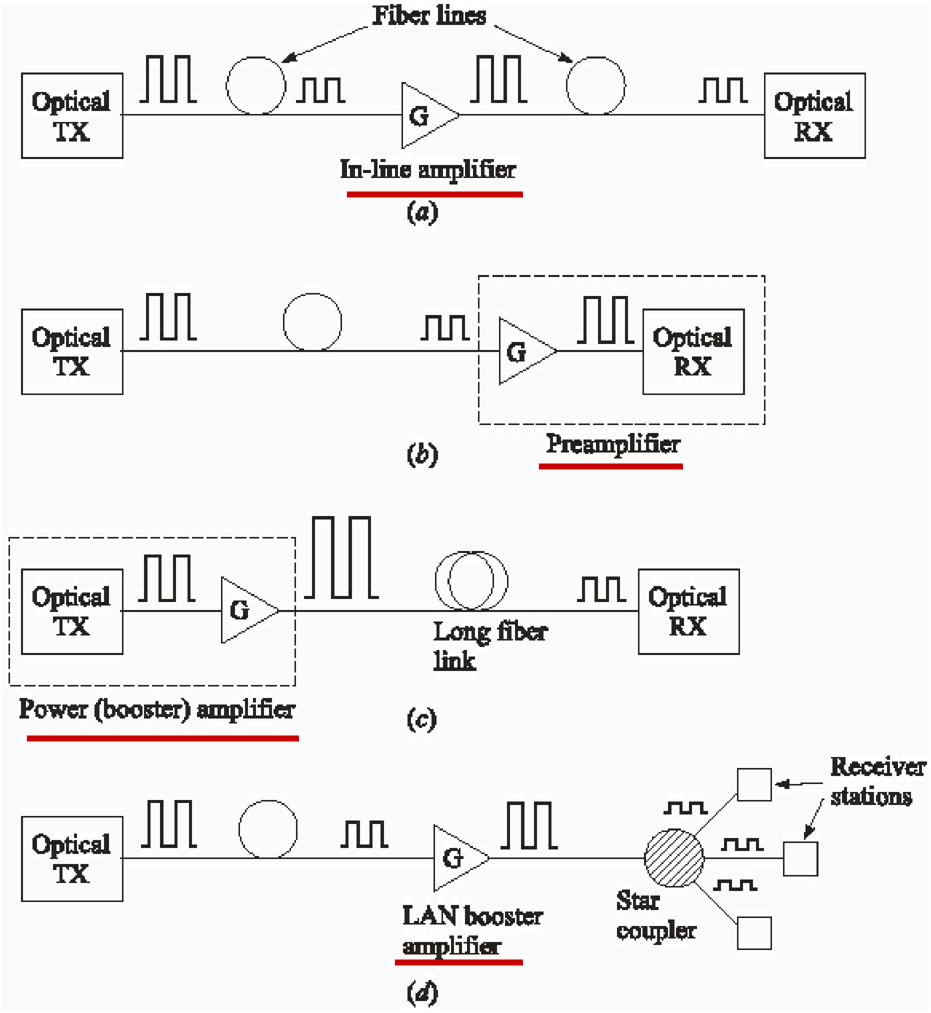


Optical Amplifier Categories

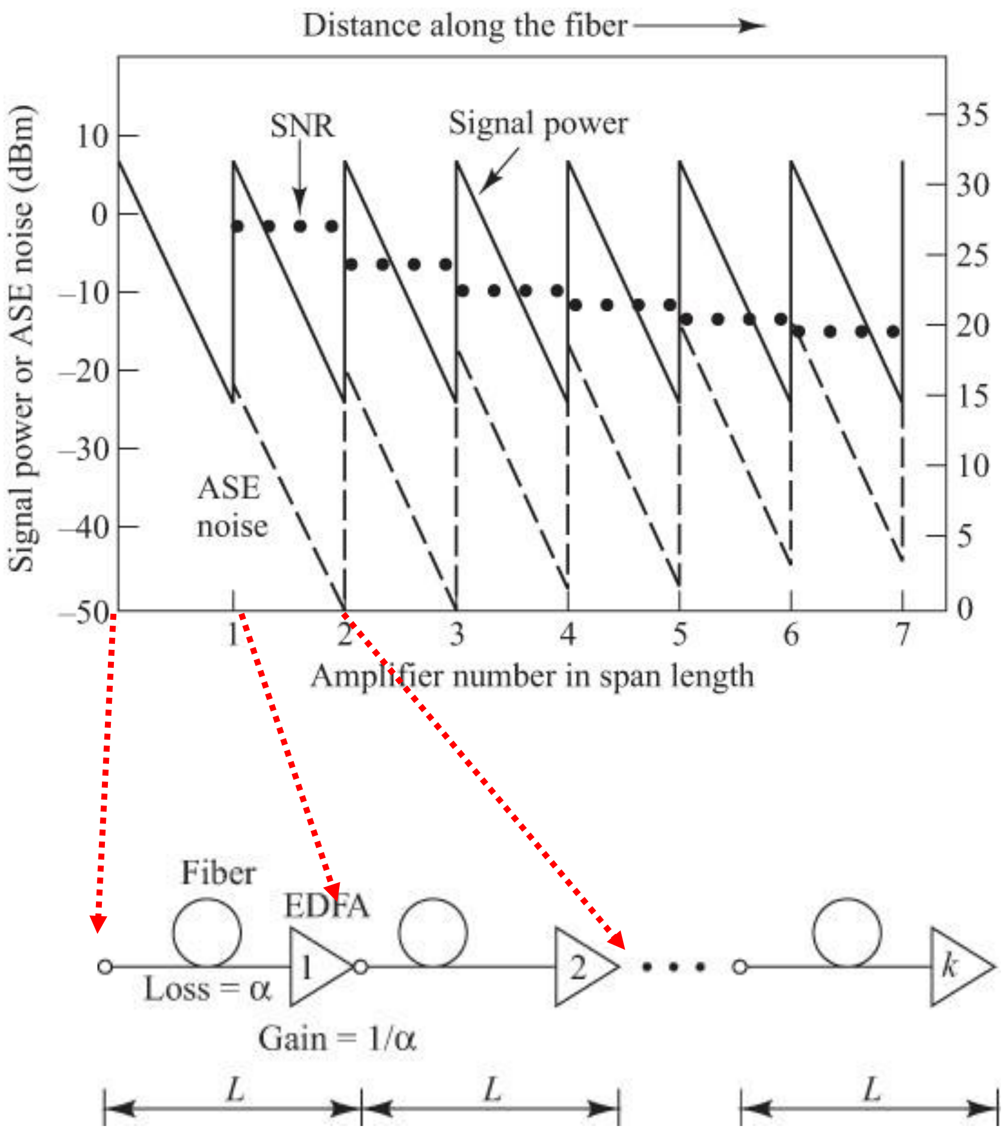
In-Line Amplifier:
High (variable) gain,
Variable inputs

Preamplifier:
High gain,
Variable inputs

Power Amplifier:
(Booster Amplifier)
Relatively low gain,
Fixed inputs



Optical Amplifier Categories



Some Possible Optical Amplifier Structures and their Spectral Operating Ranges

The three main optical amplifier types are

1. **Semiconductor optical amplifiers (SOAs)**
2. **Active fiber or doped-fiber amplifiers (DFAs)**
3. **Raman amplifiers.**

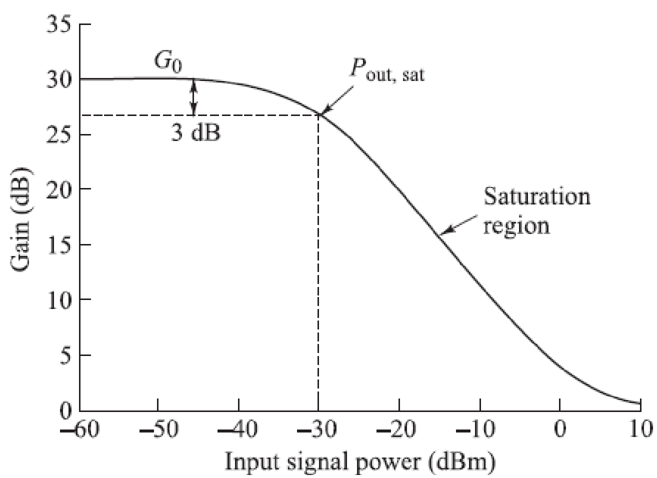
Table 11.1 *Various optical amplifier structures and their operating regions*

Acronym	*Structure*	*Operating band*
GC-SOA	Gain-clamped semiconductor optical amplifier	O- or C-band
PDFFA	Praseodymium-doped fluoride fiber amplifier	O-band
TDFA	Thulium-doped fiber amplifier	S-band
EDFA	Erbium-doped fiber amplifier	C-band
GS-EDFA	Gain-shifted EDFA	L-band
ETDFA	Er/Tm-doped tellurite (tellurium oxide) glass fiber	C- and L-bands
RFA	Raman fiber amplifier	1260 to 1650 nm

Semiconductor Optical Amplifiers

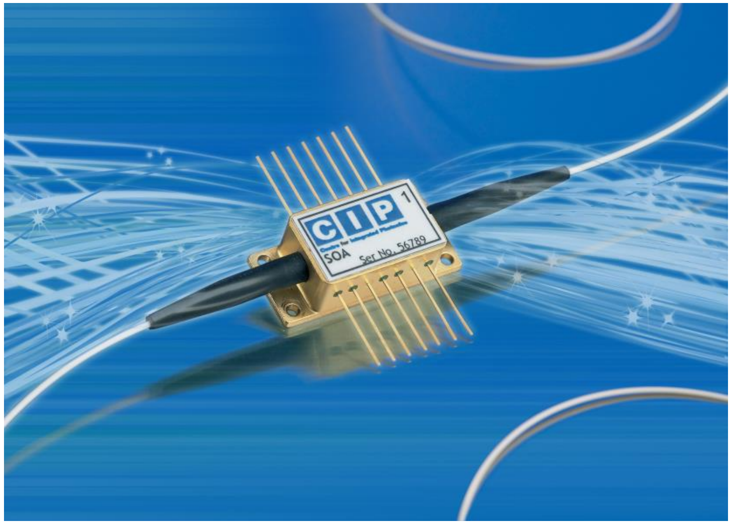
- **The SOA construction is similar to a resonator cavity of a laser diode.**
- **The SOA has an active region of length L, width w, and height d.**
- **The end facets have very low reflectivities in order for the optical signal to pass through the amplification cavity only once.**
- **External current injection is the pumping method used to create the population inversion needed for having a gain mechanism in SOAs.**
- **If the single-pass gain in the absence of light is G_0 and the amplifier saturation power $P_{amp,sat}$ is the internal power level at which the gain per unit length has been halved, then**

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

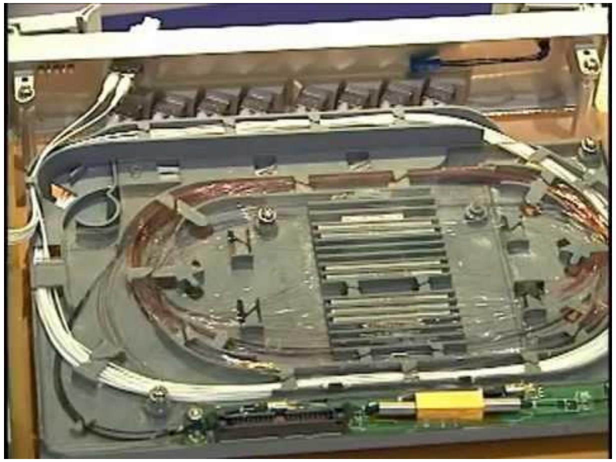


Optical Amplifiers

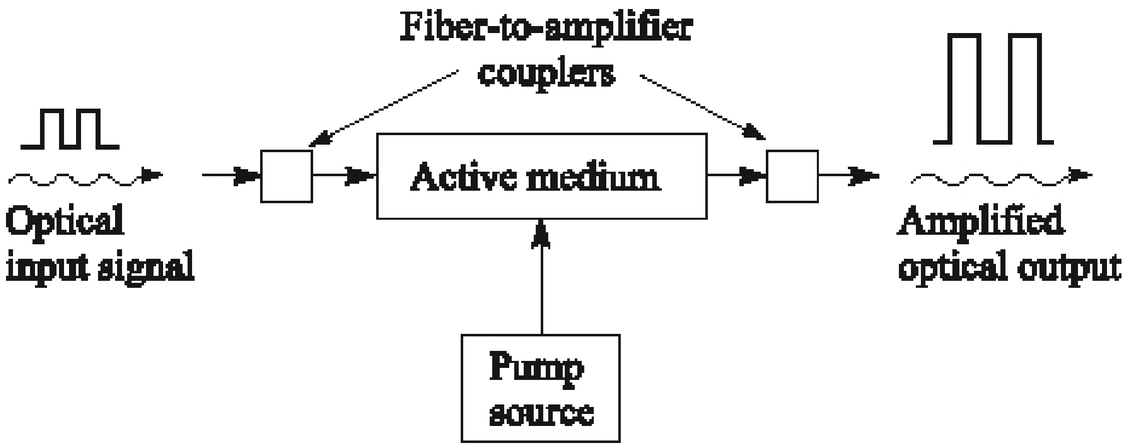
- Semicon. Opt. Amp.



- EDFA



Generic Optical Amplifier

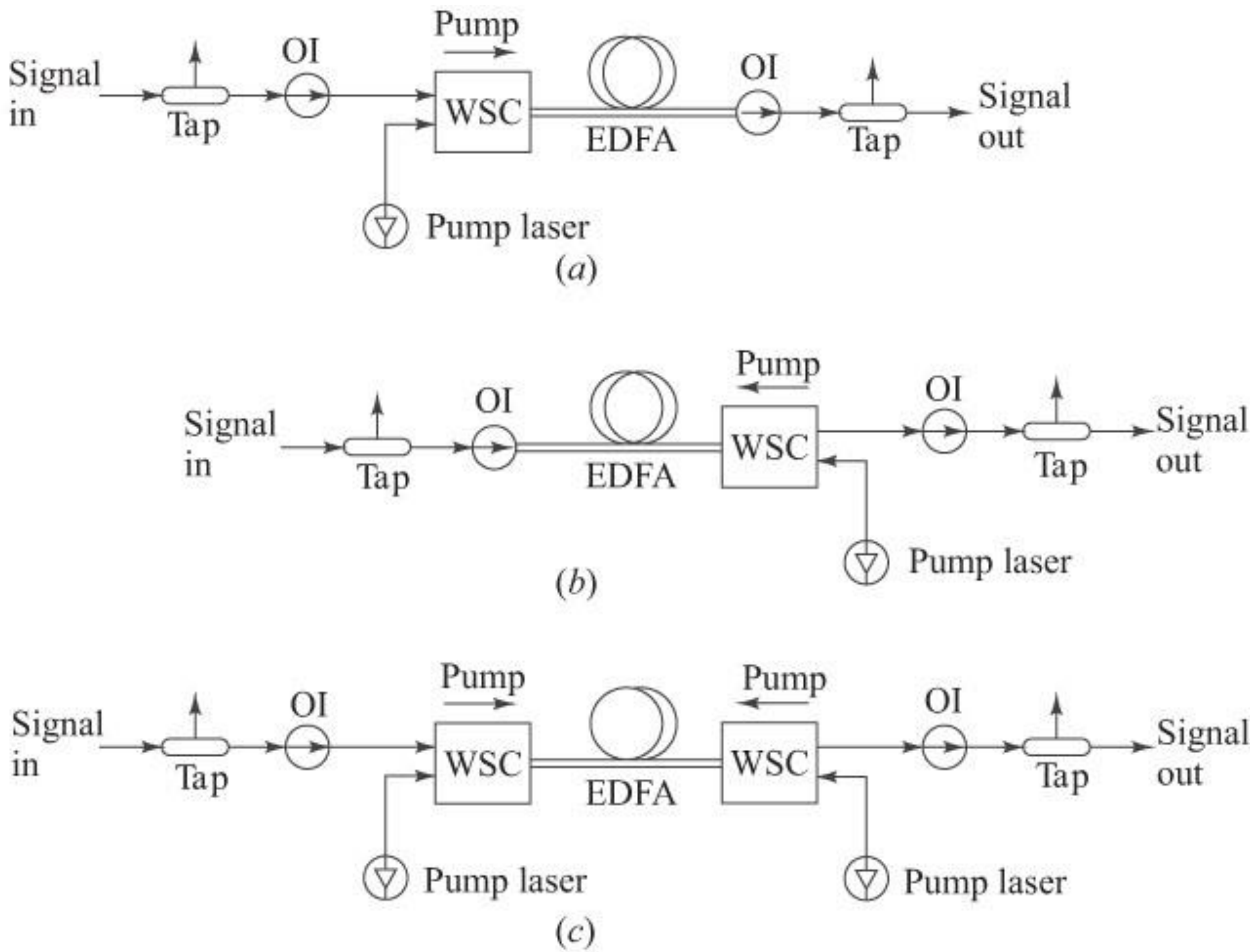


<u>Generic operation of an optical amplifier</u>:

- **An external source called a pump laser supplies energy**
- **Electrons in an active medium absorb the energy**
- **The energized electrons produce a population inversion at higher levels**
- **Signal photons entering the active medium trigger the electrons to drop to a lower energy level thereby releasing many identical photons**

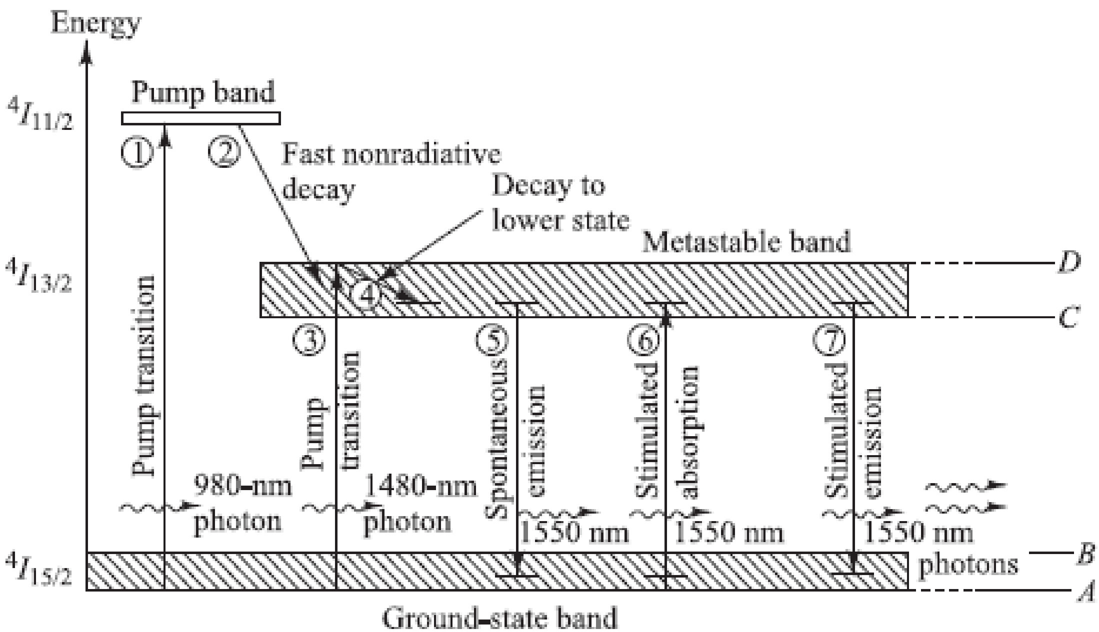
One example of an active medium is an <u>erbium-doped optical fiber</u>

Generic Optical Amplifier



OI: Optical isolator
WSC: Wavelength-selective coupler

Erbium Energy-Level Diagram



There are seven basic transition processes in an optical amplifier:

(1) and (3): 980- and/or 1480-nm pump photons boost electrons to higher levels

(2) and (4): Decay processes from pump levels drop electrons to amplifier levels

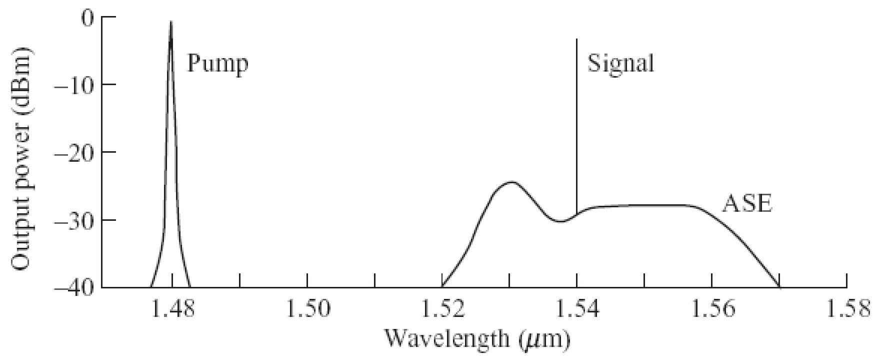
(5): Spontaneous emission produces optical noise photons

(6): Stimulated absorption depletes the signal level

(7): Stimulated emission boosts the signal level

Amplifier Noise

- **The dominant noise generated in an optical amplifier is called *amplified spontaneous emission* (ASE) *noise*.**
- **Results from *spontaneous recombination* of electrons and holes in the amplifier medium**
  - **The recombination occurs over a wide range of electron-hole energy differences**
  - **The result is a broad spectral background of noise photons that get amplified as they travel through the EDFA.**
- **Example 1480-nm pump spectrum and a output signal at 1540 nm with the associated ASE noise**



Optical SNR

- In a transmission link with optical amplifiers, the light signal entering the receiver contains ASE noise from the cascade of optical amplifiers.
- Need to evaluate the *optical signal-to-noise ratio (OSNR)*.
- OSNR is the ratio of the average EDFA optical signal output power P_{ave} to the unpolarized ASE optical noise power P_{ASE}:

$$\boxed{\mathrm{OSNR} = \frac{P_{\mathrm{ave}}}{P_{\mathrm{ASE}}}}$$

or, in decibels

$$\boxed{\mathrm{OSNR(dB)} = 10 \log \frac{P_{\mathrm{ave}}}{P_{\mathrm{ASE}}}}$$

OSNR versus Q

Derived relationship between OSNR and the Q parameter

$$Q = \frac{2\sqrt{2}\,\mathrm{OSNR}}{1 + \sqrt{1 + 4\,\mathrm{OSNR}}}$$

Solving for OSNR yields

$$\boxed{\mathrm{OSNR} = \frac{1}{2} Q\left(Q + \sqrt{2}\right)}$$

Example 11.6 In Chapter 7 it is shown that to achieve a BER = 10^{-9} the factor Q must be 6. What is the OSNR for this BER?

Solution: Using Eq. (11.38) then yields

$$\mathrm{OSNR}\ (\mathrm{BER} = 10^{-9}) = 0.5(6)(6 + \sqrt{2}) = 22.24 \approx 13.5\ \mathrm{dB}$$

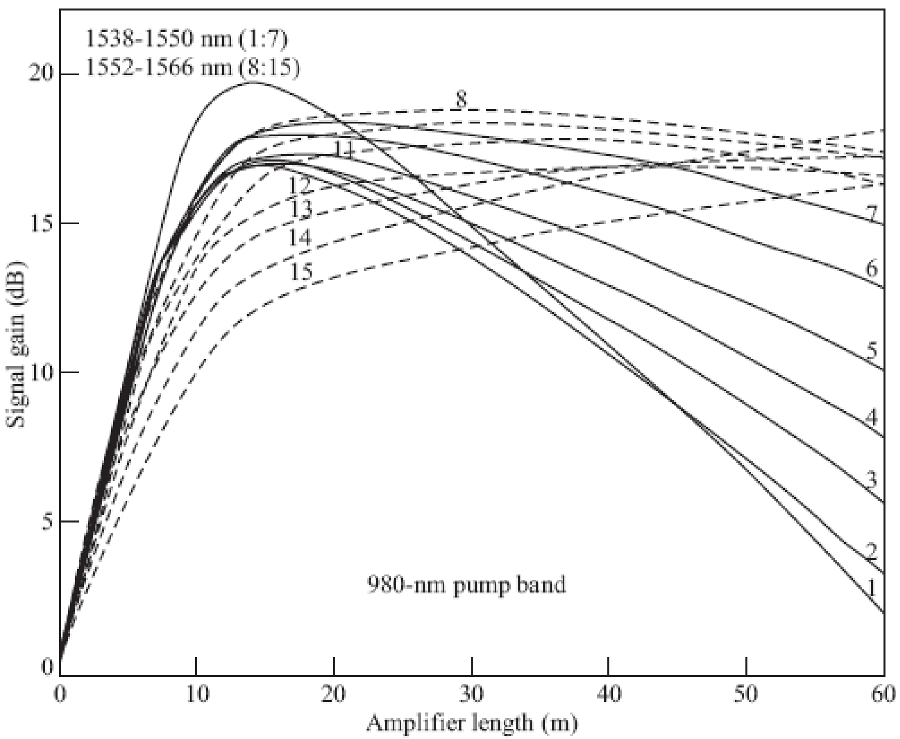
Therefore if an OSA measures an OSNR ≤ 13.5 dB, then the corresponding error rates are equal to or higher than BER = 10^{-9}.

EDFA Gain versus Wavelength

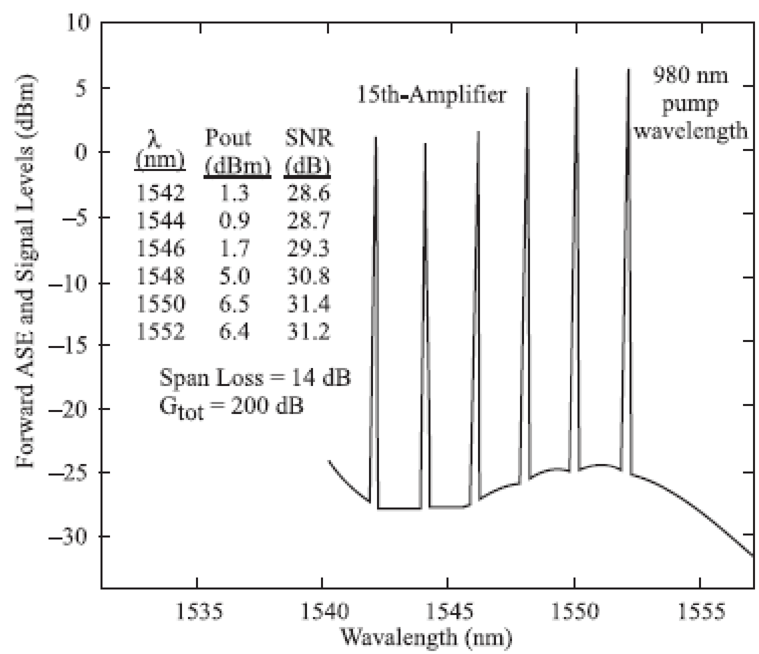
(From: Ali, Elrefaie, Wagner, Ahmed, *J. Lightwave Technol*., vol. 14, pp, 1436-1448, 1996)

Power gain versus amplifier length

- **Maximum-gain length is longer for higher wavelengths**
- **For a specific amplifier length the gains vary with λ**
  - **This produces a gain skew among different wavelengths**

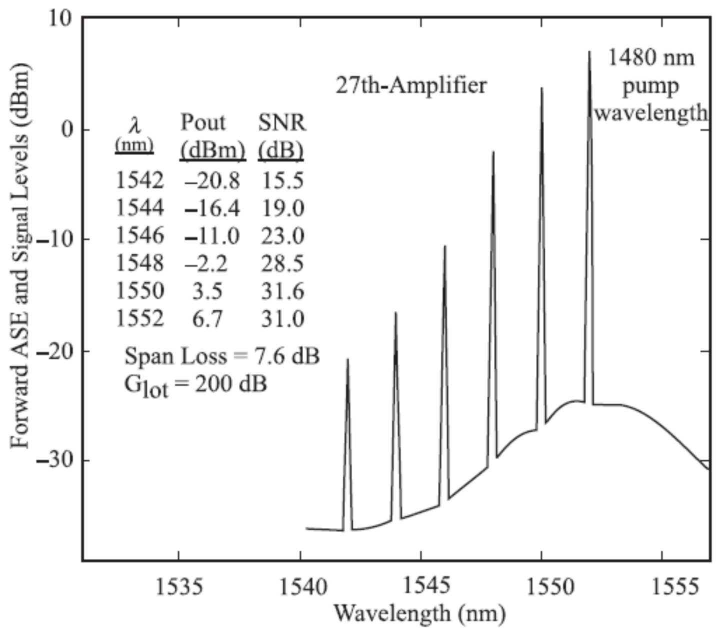


From Ref. 22



Gain of Cascaded Amplifiers

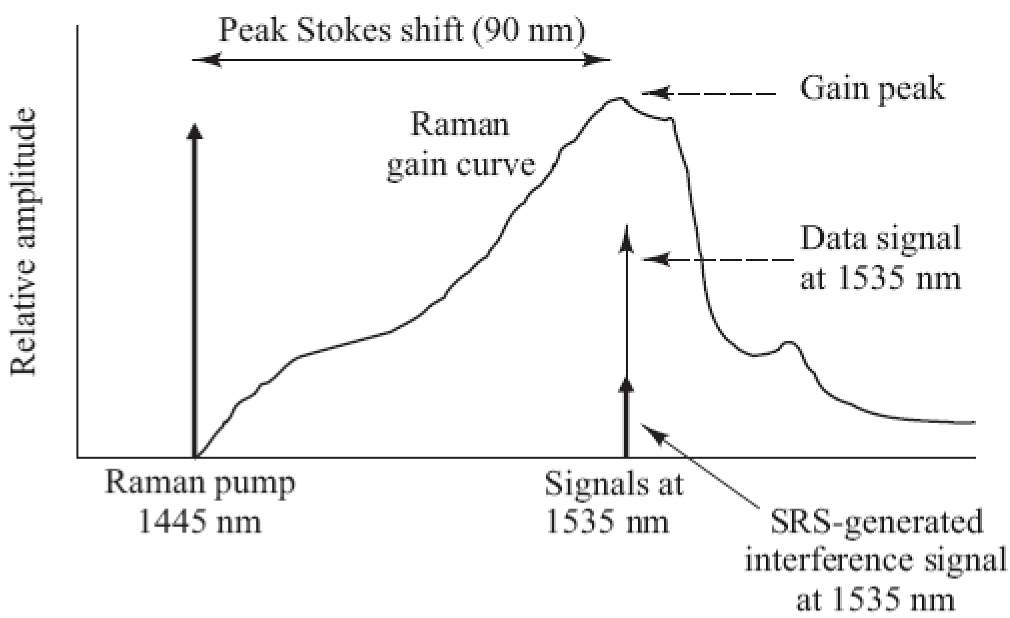
- **EDFA gain is wavelength-dependent in the normal 1530-to-1560-nm EDFA operating window**
- **Gains of 6 wavelengths after a cascade of 27 optical amplifiers**
- **This gain variation must be equalized**
  - **Otherwise large SNR differential will appear among the channels after the wavelengths pass through a series of several EDFAs**



From Ref. 22

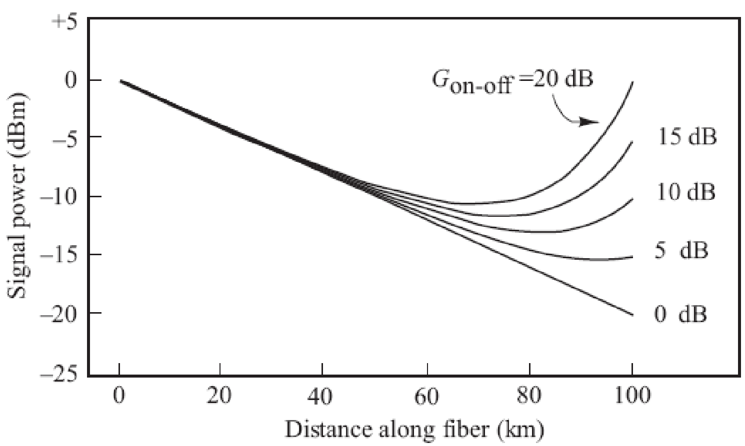
Raman Amplifiers

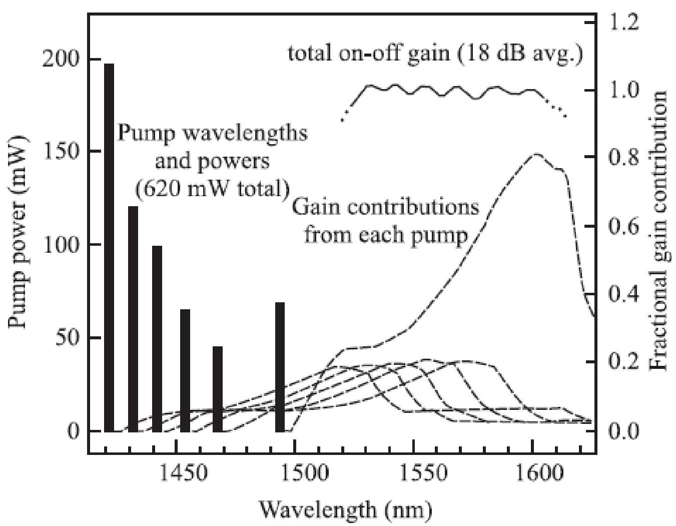
- A ***Raman optical amplifier*** **is based on the nonlinear effect** ***stimulated Raman scattering (SRS)*****, which occurs in fibers at high optical powers**
- **An interaction between an optical energy field and the vibrational modes of the material lattice structure transfers power to higher wavelengths over a broad spectral range of 80 to 100 nm**
- **The shift to a particular longer wavelength is called the** ***Stokes shift***



Distributed Raman Amplifier Application

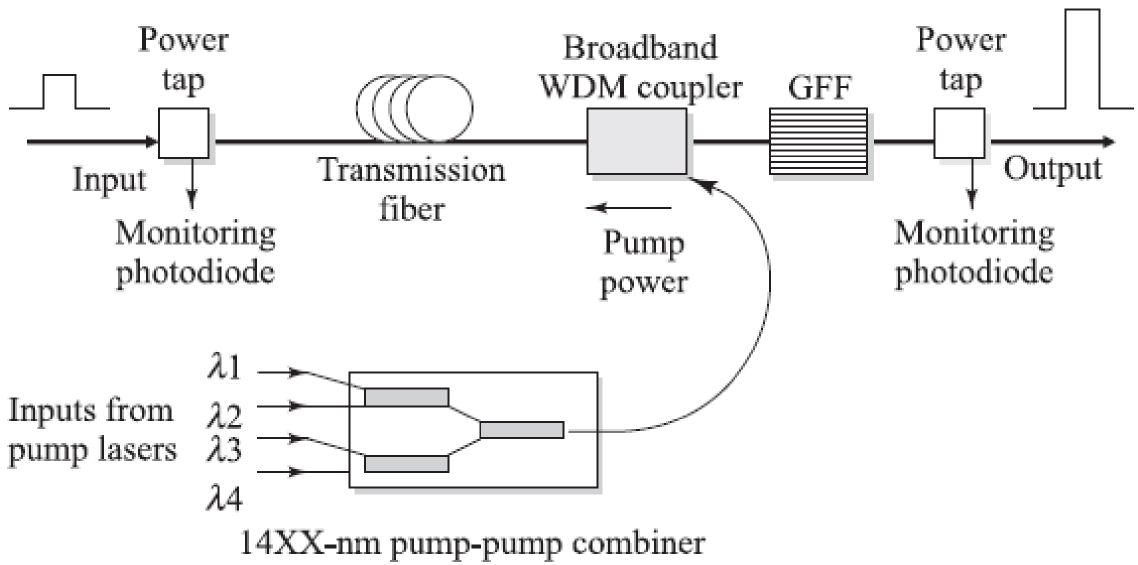
- **A Raman amplifier makes use of the standard transmission fiber itself as the amplification medium.**
- **For the *distributed Raman amplifier*, optical power from one or more Raman pump lasers is inserted into the far end of the transmission fiber toward the transmitting end.**
- **Thereby the final 20 to 40 km of the transmission fiber is converted into a preamplifier.**





Raman Amplifier Setup

- ***Pump lasers*** **with high output powers in the 1400-to-1500-nm region are required for Raman amplification of C- and L-band signals.**
- **A *pump-power combiner* multiplexes the outputs from pump lasers operating at different wavelengths onto a single fiber.**
- **Examples might be 1425, 1445, 1465, and 1485 nm.**
- **The *gain flattening filter* (GFF) equalizes the gains at different λs.**



Raman Amplifier Components

- **Pump lasers that provide fiber-launch powers of up to 500 mW are available in standard 14-pin butterfly packages.**
- **Pump-power couplers are called *14XX-nm pump-pump combiners.***

Table 11.2 *Performance parameters of a 14XX-nm pump-pump combiner based on fused-fiber coupler technology*

Parameter	*Performance value*
Device technology	Fused-fiber coupler
Wavelength range	1420 to 1500 nm
Channel spacing	Customized: 10 to 40 nm Standard: 10, 15, 20 nm
Insertion loss	< 0.8 dB
Polarization dependent loss	< 0.2 dB
Directivity	>55 dB
Optical power capability	3000 mW

Table 11.3 *Performance parameters of broadband WDM couplers for combining 14XX-nm pumps and C-band or L-band signals*

Parameter	*Performance value*	*Performance value*
Device technology	Micro-optics	Thin-film filter
Reflection channel λ range	1420 to 1490 nm	1440 to 1490 nm
Pass channel λ range	1505 to 1630 nm	1528 to 1610 nm
Reflection channel insertion loss	0.30 dB	0.6 dB
Pass channel insertion loss	0.45 dB	0.8 dB
Polarization dependent loss	0.05 dB	0.10 dB
Polarization mode dispersion	0.05 ps	0.05 ps
Optical power capability	2000 mW	500 mW

Wideband Optical Amplifiers

- A combination of two amplifier types can provide amplification in both the C- and L-bands or in the S- and C-bands. Three amplifier types can provide signal gains in the S-, C-, and L-bands or other combinations.
- The amplifiers could be based on thulium-doped silica fibers for the S-band, standard EDFAs for the C-band, gain-shifted EDFAs for the L-band
- Different versions of Raman amplifiers also can be used
- The amplifier combinations can be in parallel or in series.

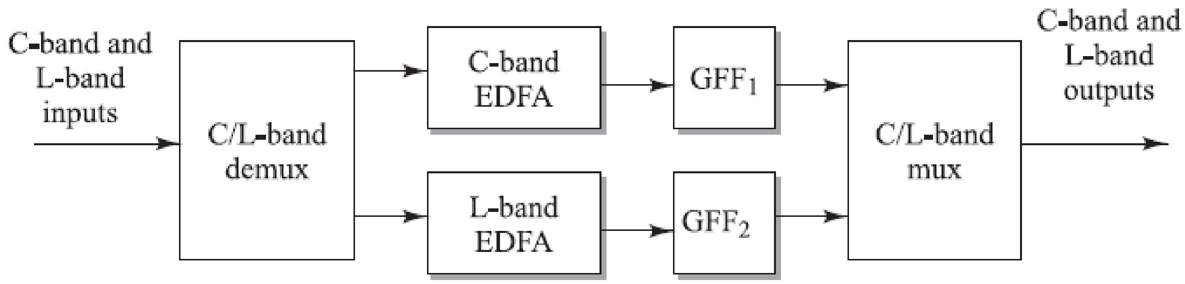


Fig. 11.22 *Representation of two different band optical amplifiers in parallel*

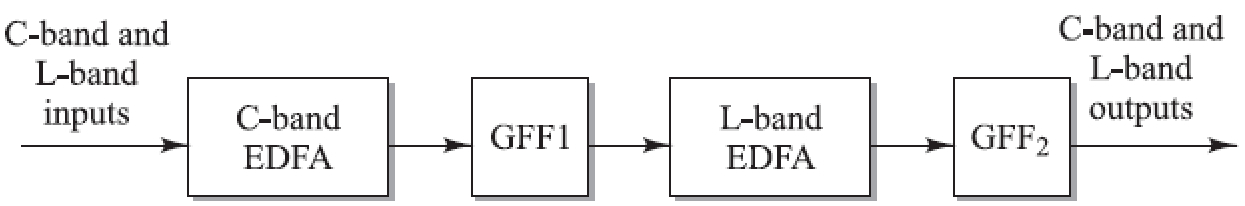


Fig. 11.23 *Representation of two different band optical amplifiers in series*