TKK Tietoliikennelaboratorio
HUT Communications Laboratory

S-72.3340 Optical Networks Course

Lecture 2: Essential Building Blocks

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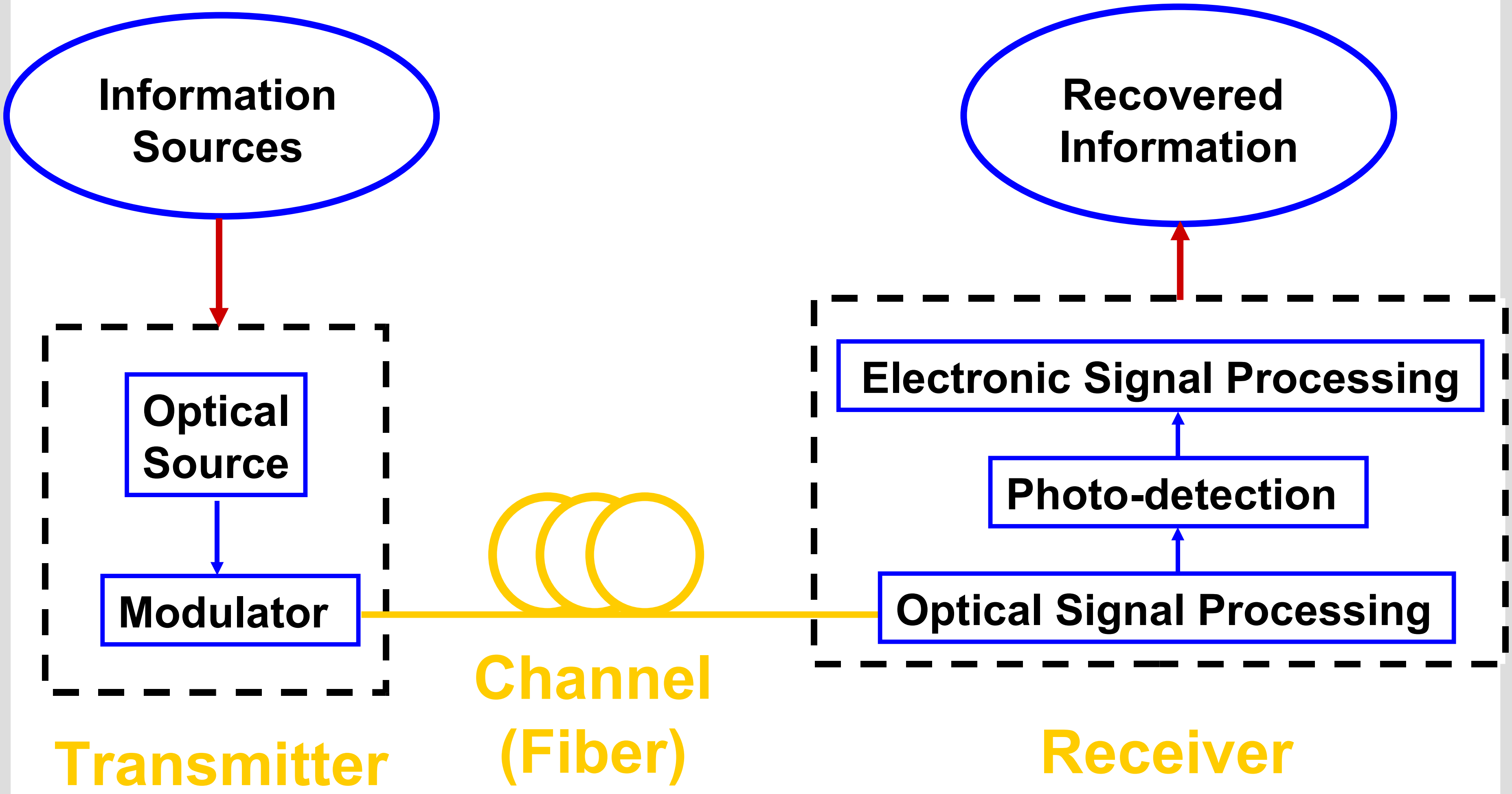
Lecture Highlights

- Optical sources/transmitters
- Photodetectors/receivers
- Optical amplifiers
- Passive devices
  - Filters, splitters etc.

1. Introduction

- A fiber-optic communications link is composed of various essential building blocks
  - Previous lecture focused mainly of the actual fiber transmission medium
  - This lecture ⇒ gentle overview of various optical devices
- To transport an information bearing signal (initially in electrical format) over fiber you need to:
  - 1) convert signal to an optical signal before carrying it on fiber
  - 2) convert optical signal to electrical format to retrieve the data

1. Introduction



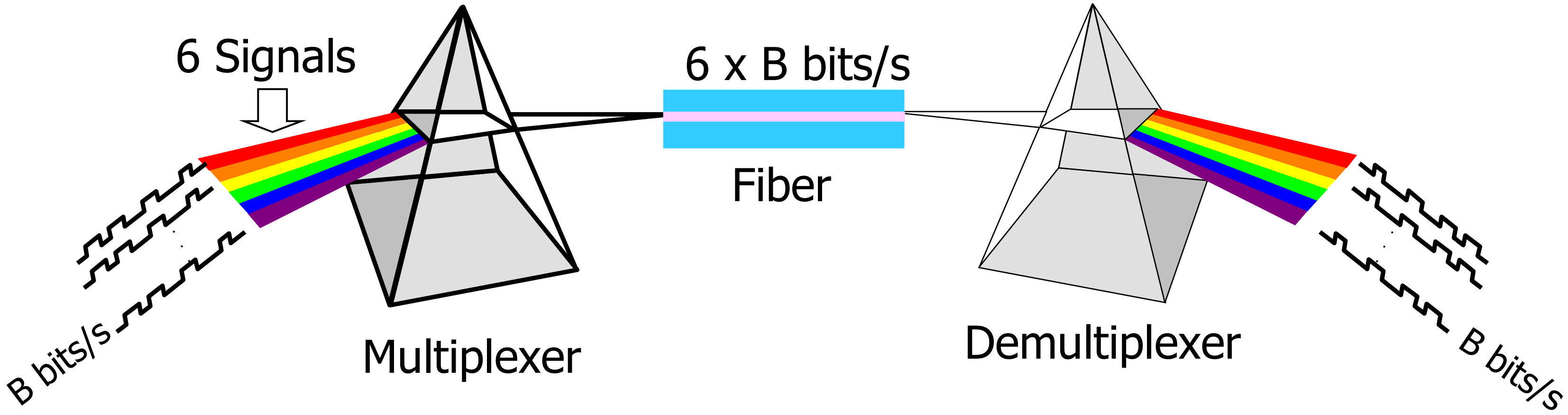
1. Introduction

- Operating wavelength range of optical devices must match that of fiber medium
  - Several wavelength bands designated by ITU-T in the 1260-1675 nm range
  - E-band also known as S^+-band and U-band also known as L^+-band
  - Multiwavelength operation is possible

Band	Descriptor	Wavelength range (nm)
O-band	Original	1260 to 1360
E-band	Extended	1360 to 1460
S-band	Short	1460 to 1530
C-band	Conventional	1530 to 1565
L-band	Long	1565 to 1625
U-band	Ultra-long	1625 to 1675

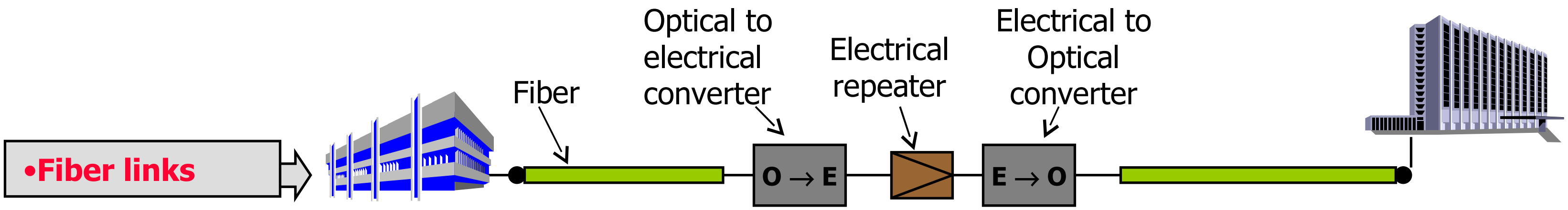
2. Wavelength-Division Multiplexing

- Wavelength-division multiplexing or WDM
  - Frequency-division multiplexing in the optical domain
  - Multiple information-bearing optical signals transported on a single strand of fiber



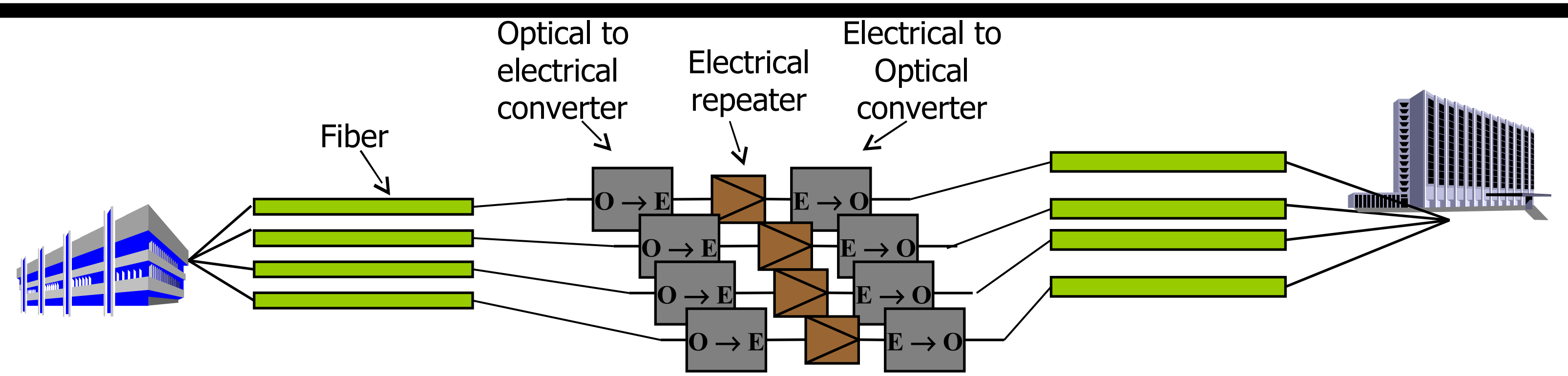
2. Wavelength-Division Multiplexing

❑ Simple point-to-point link

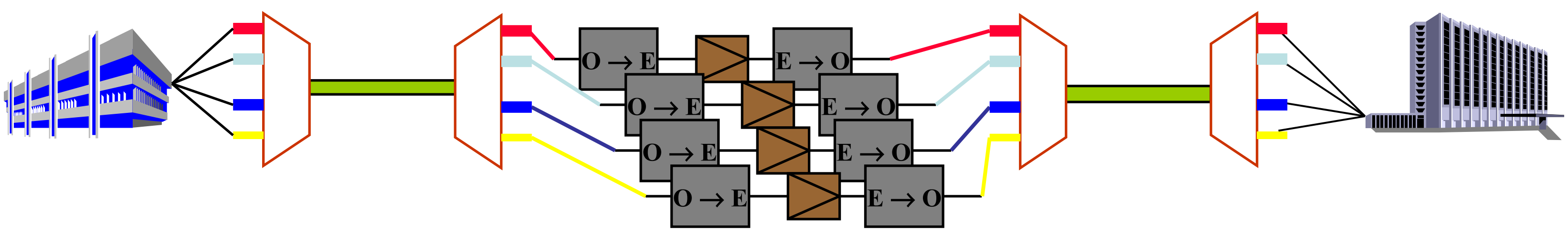


- New service demands and users, create need for extra link capacity. How do you quadruple the existing ”fiber capacity”?

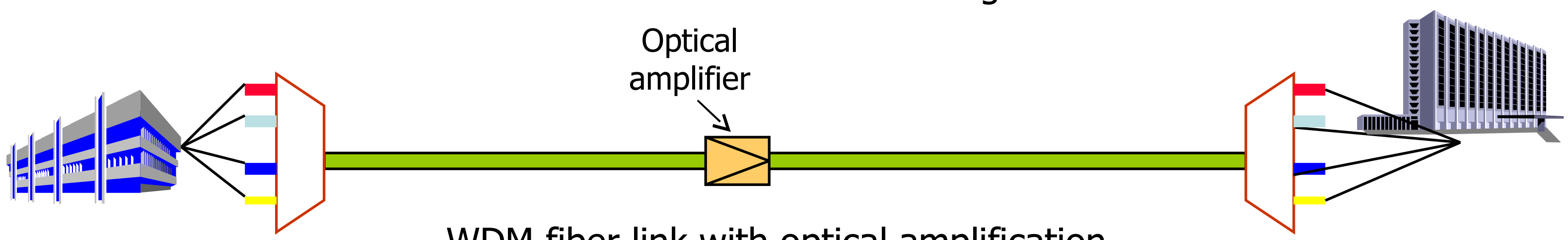
2. Wavelength-Division Multiplexing



Space-division multiplexing fiber link with electrical regeneration



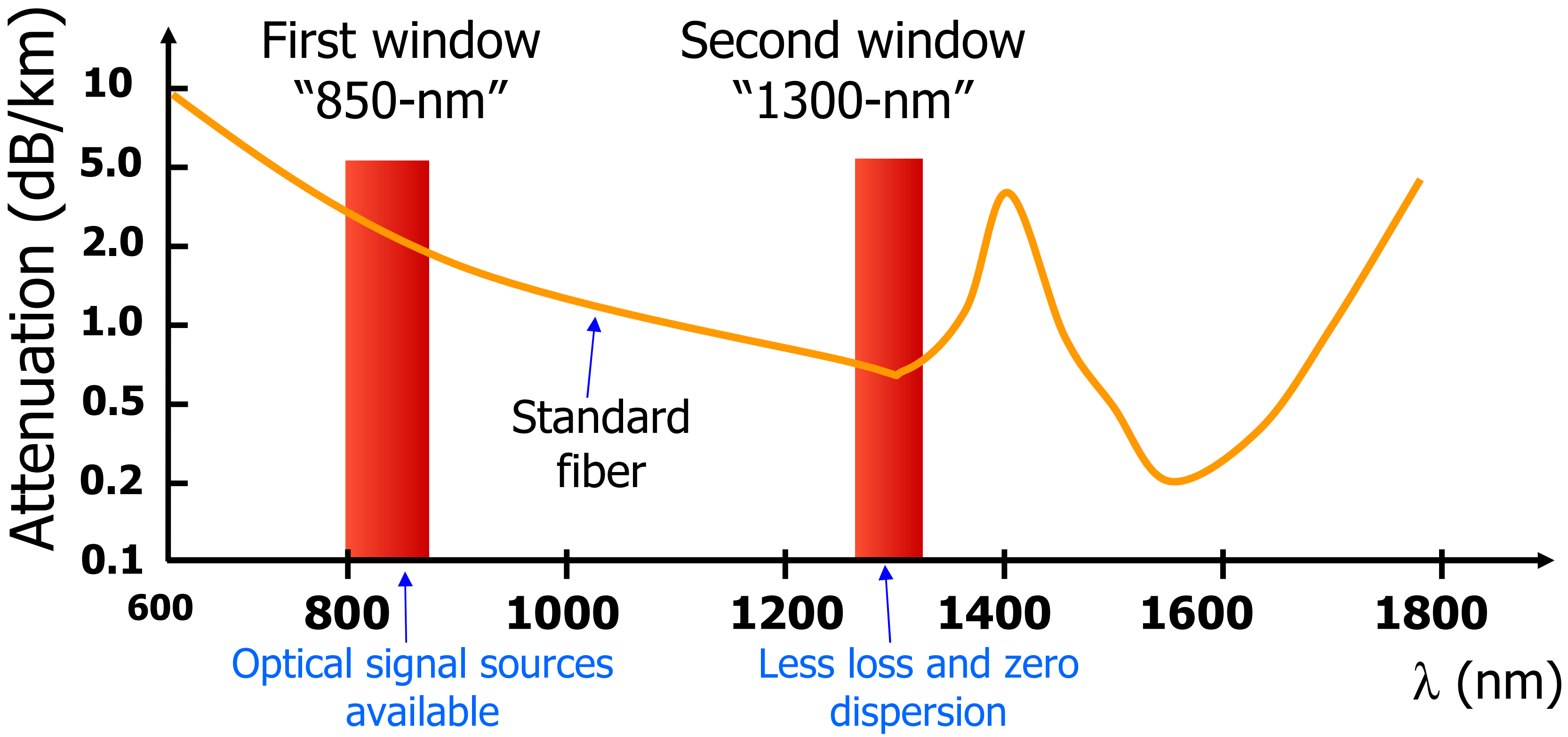
WDM fiber link with electrical regeneration



WDM fiber link with optical amplification

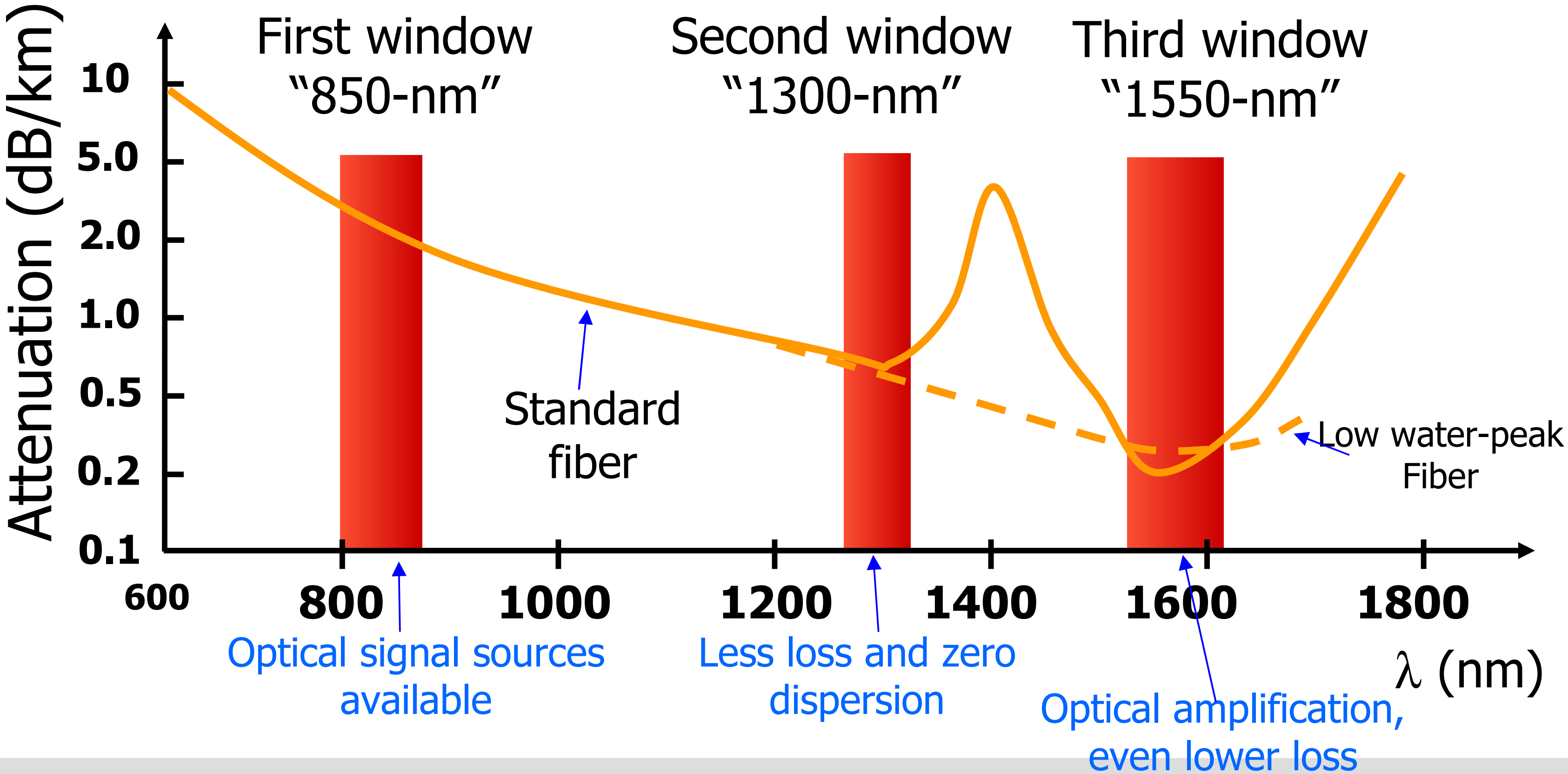
2.1 Single Wavelength Systems

- Early optical communication systems
  - Lack of optical amplification
  - Single 850 nm or 1300 nm wavelength of operation



2.2 WDM Systems

- Amplified optical communications systems
  - Optical amplification enables WDM in 1550 nm window
  - Less attenuation than 850 nm and 1300 nm windows



2.3 Types of WDM

- Two main types of WDM
  - Dense WDM
  - Coarse WDM

2.3 Types of WDM

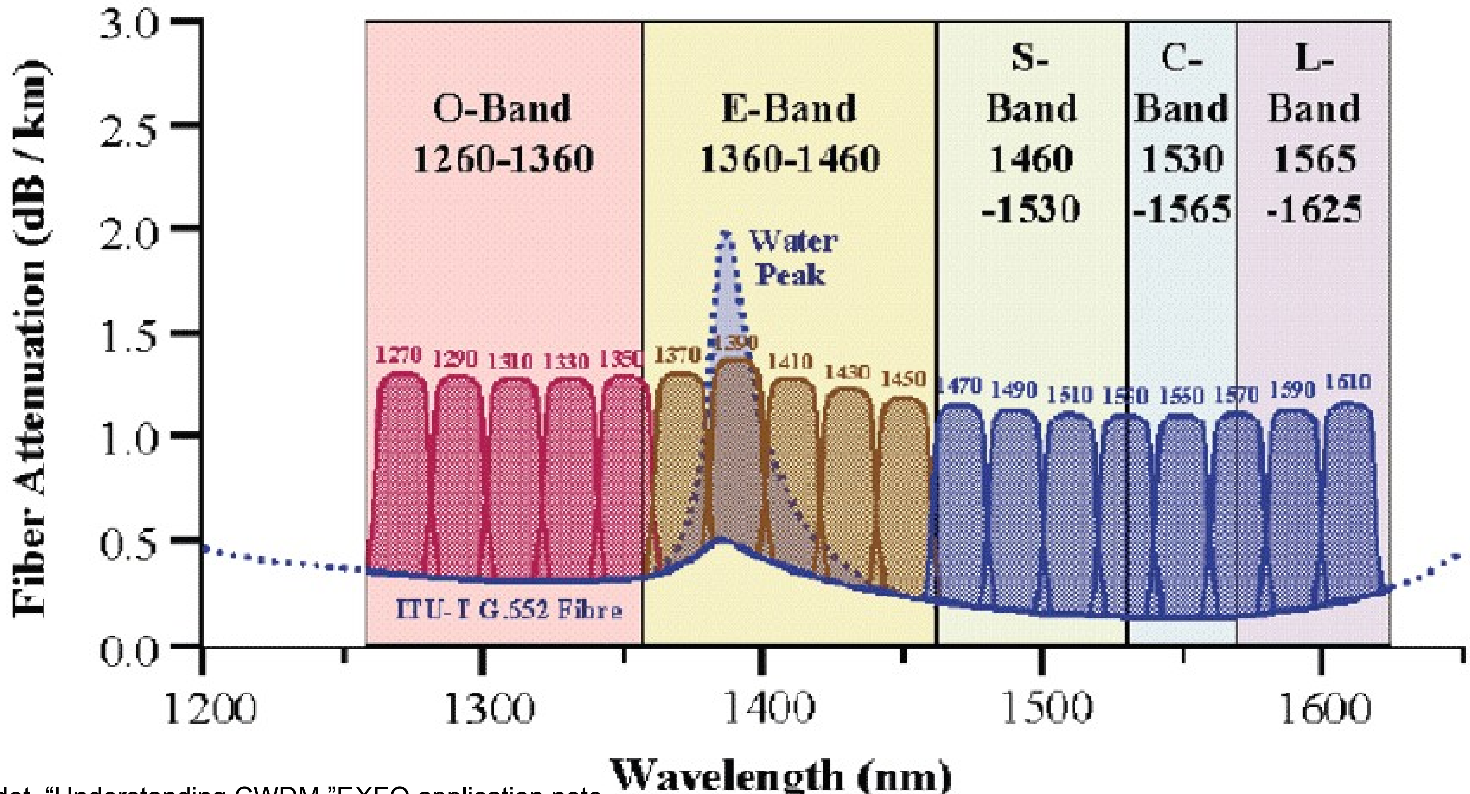
- Two main types of WDM: DWDM and CWDM
- Dense WDM (DWDM)
  - ITU-T G.694.1 grid with channel spacing ≤ 200 GHz or ≤ 1.6 nm
  - 10s or 100s of channels in C- and L-bands (1530-1625 nm)

frequency (THz)	wavelentgh (nm)
192,100	1560,61
192,150	1560,20
192,200	1559,79
192,250	1559,39
192,300	1558,98
192,350	1558,58
192,400	1558,17
192,450	1557,77
192,600	1556,55
192,650	1556,15
192,700	1555,75
192,750	1555,34
192,800	1554,94
192,850	1554,54
192,900	1554,13
192,950	1553,73
193,100	1552,52
193,150	1552,12
193,200	1551,72
193,250	1551,32
193,300	1550,92
193,350	1550,52
193,400	1550,12
193,450	1549,72
193,600	1548,51
193,650	1548,11
193,700	1547,72
193,750	1547,32
193,800	1546,92
193,850	1546,52
193,900	1546,12
193,950	1545,72

Figure: Excerpt of ITU-T G.694.1 grid

2.3 Types of WDM

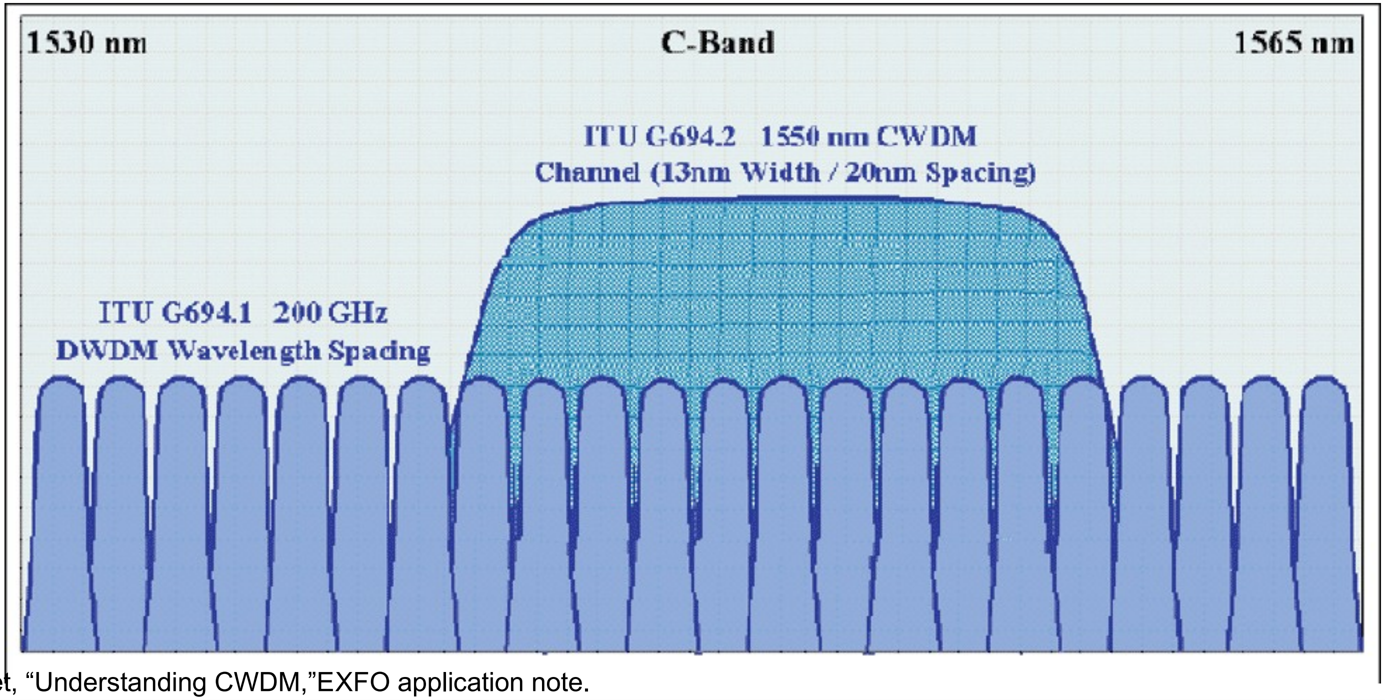
- Coarse WDM (CWDM)
  - ITU-T G.694.2/695 grid with 2500 GHz or 20 nm channel spacing
  - 18 channels spanning O-, E-, S-, C- and L-bands (1260-1625 nm)



Source: F. Audet, "Understanding CWDM,"EXFO application note.

2.3 Types of WDM

- DWDM enables many channels with amplification,
  - ...but requires stable transmitters and good filtering (sharp skirts and precise center frequency)
- CWDM simplifies filter and transmitter design (cheaper)
  - ...but no amplification and few channels enables



Source: F. Audet, “Understanding CWDM,”EXFO application note.

3. Optical Signal Sources

- Two main sources: LEDs and lasers
- Light Emitting Diodes (LEDs)
  - Cheap sources ⇒ easy to fabricate and use
  - Large spot size for coupling to multimode fibers (62.5 μm core)
  - Suitable only for low rate applications and short distances
- Lasers
  - Light amplification by stimulated emission of radiation
  - Small concentrated spot size for coupling to singlemode fibers (8-9 μm core)
  - Enables longer distances and higher data rates
  - Costly ⇒ more complex and difficult to fabricate

3.1 Advantages of Lasers

- Lasers can be modulated (switched ON and OFF) at high speeds
  - Speed ⇒ rise or fall time taken to go from 10% to 90% of peak power
  - Lasers achieve data rates in terms of Gbit/s
  - LEDs limited to a few hundred Mbit/s

3.1 Advantages of Lasers

- Lasers are energy efficient
  - LEDs light output linearly proportional to drive current (50 to 100 mA)
  - Laser light output proportional to current above the threshold (5 to 40 mA)

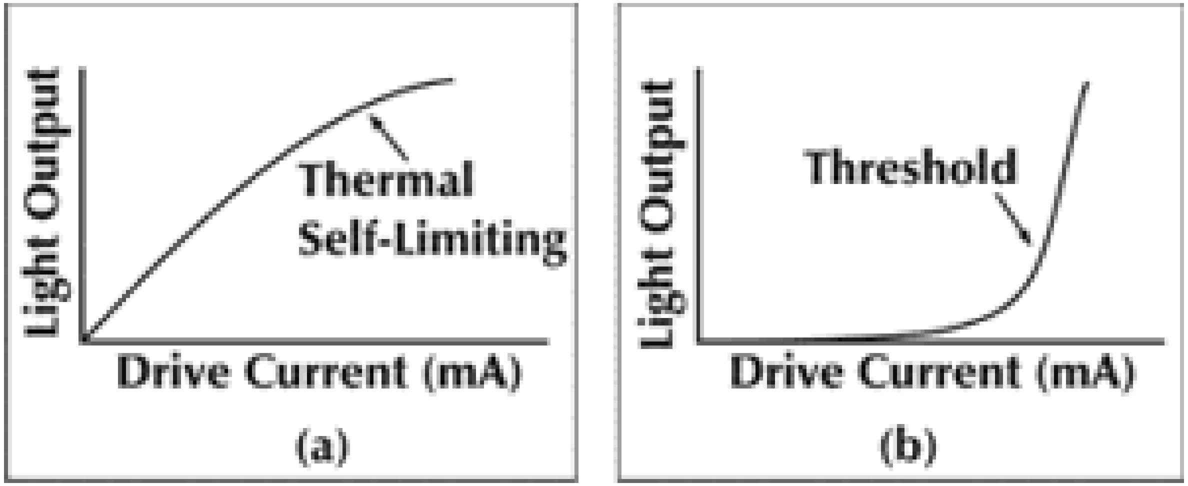
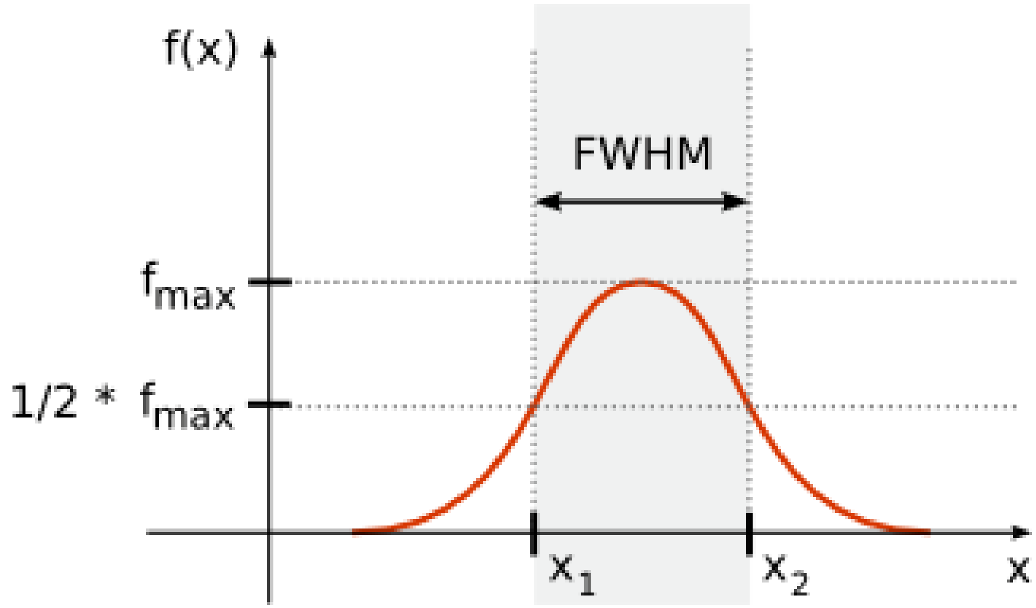


Figure: Relative amount of light output versus electrical drive current for (a) LEDs and (b) lasers

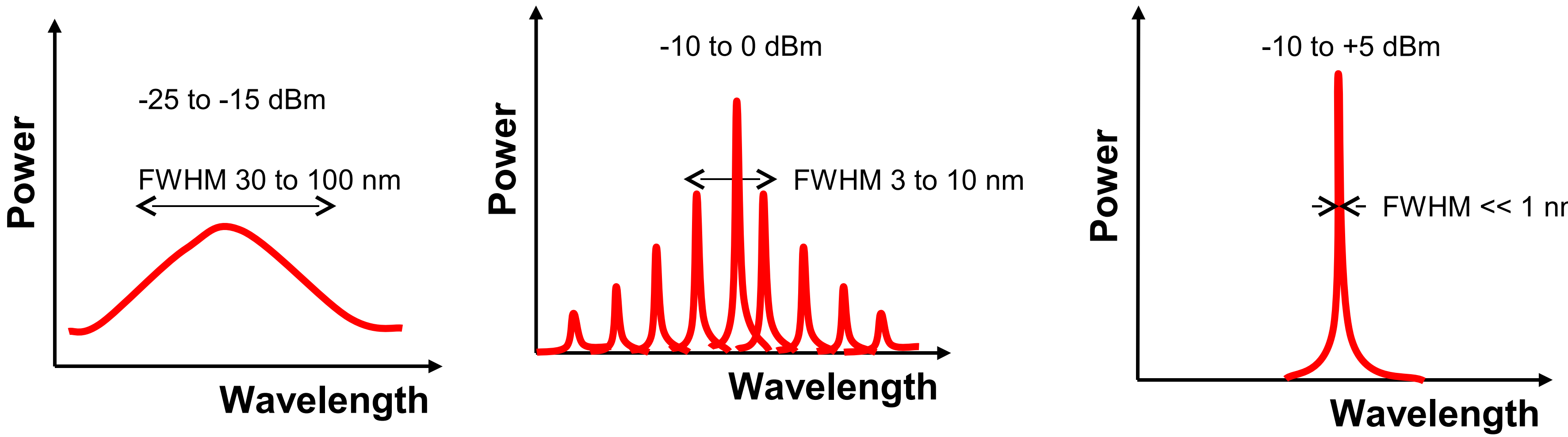
3.1 Advantages of Lasers

- Lasers have more suitable spectra
  - Ideally all light emitted is at peak wavelength…but
  - In practice output at range of wavelengths around peak
  - Wavelength range measured by spectral linewidth
    - Usually represented by the full width half maximum (FWHM)
    - To crosstalk in WDM systems (channel spacing ≥ FWHM)



3.1 Advantages of Lasers

- Lasers have narrower spectral linewidths than LEDs
- Laser oscillate simultaneously in several wavelengths or longitudinal modes
    - Two laser types: Multiple-longitudinal mode (MLM) lasers and Single-longitudinal mode (SLM) lasers
    - High side-mode suppression ratio in SLM lasers ⇒ only main mode is prominent



LED spectrum | MLM laser spectrum | SLM laser spectrum

3.1 Advantages of Lasers

- Compact semiconductor lasers preferred for implementing transmitters in optical networks
  - Unpackaged: ~ grain of salt, 0.5mm × 200mm × 100mm
  - Packaged: ~ 2×1×1 cm

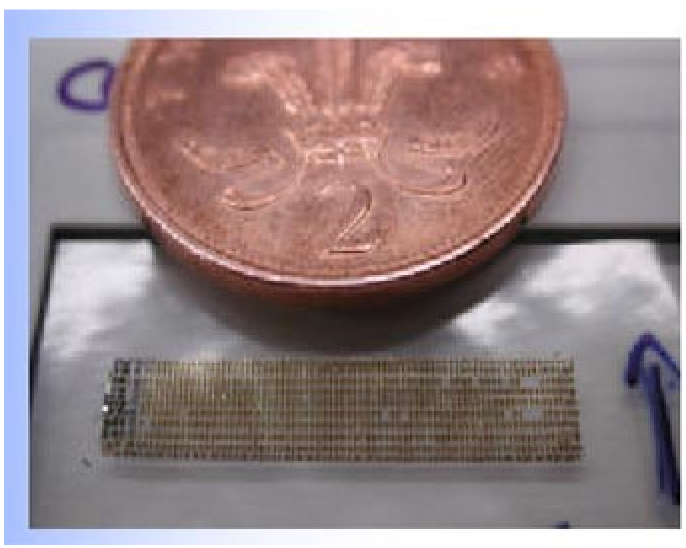


Figure: Array of about 1000 lasers grown on a wafer

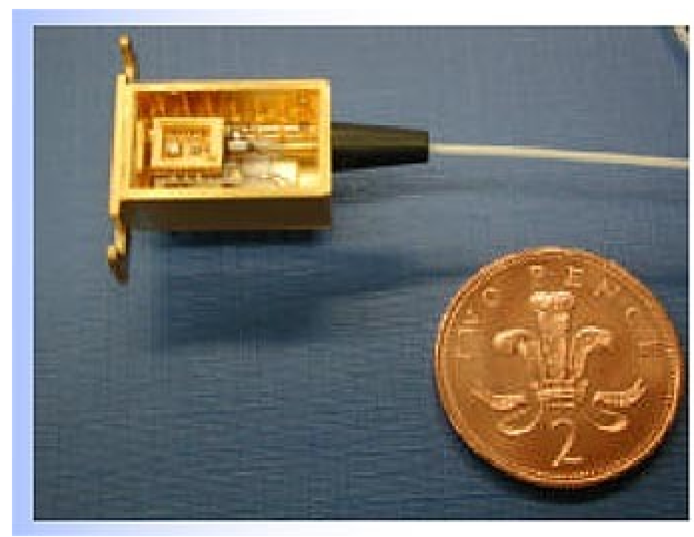
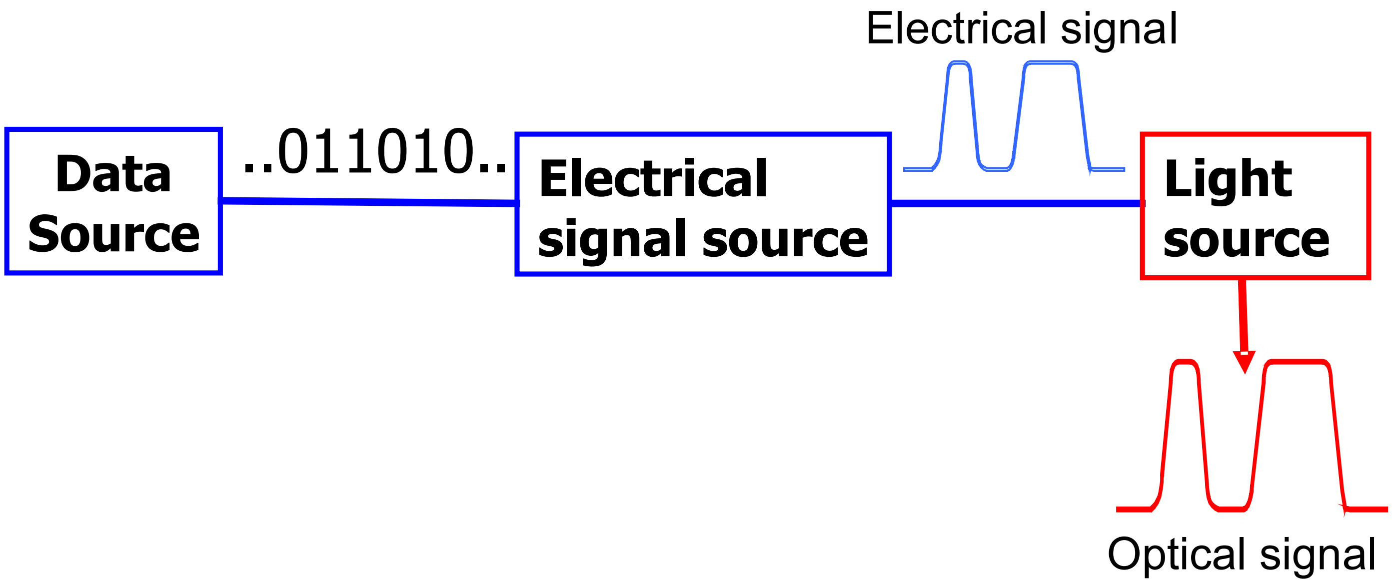


Figure: Packaged laser with a fiber pigtail

3.2 How do Lasers Produce Light?

- Converting an electrical to optical signal

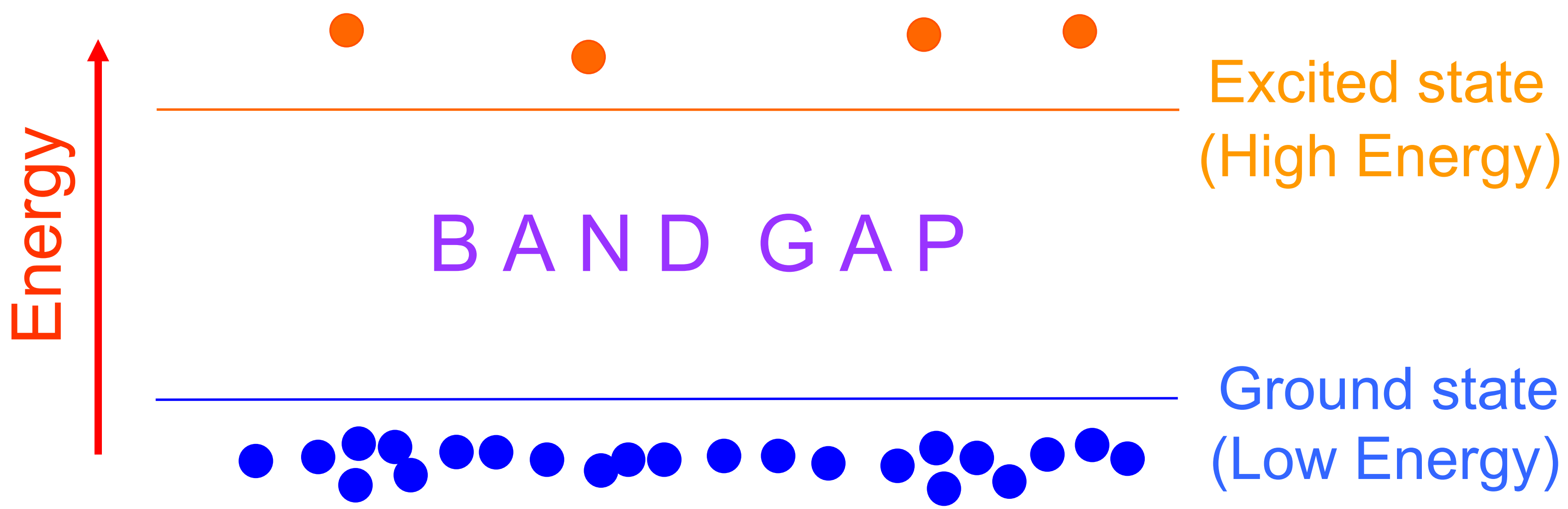


  - Use stream of electrons to produce stream of photons

3.2 How do Lasers Produce Light?

- Physical systems (e.g. atoms, electrons, ions) found in one of a discrete number of energy levels
  - Highest (excited state) and lowest (ground state) levels
  - Energy difference between the two levels ⇒ Band gap

Figure: Energy level diagrams



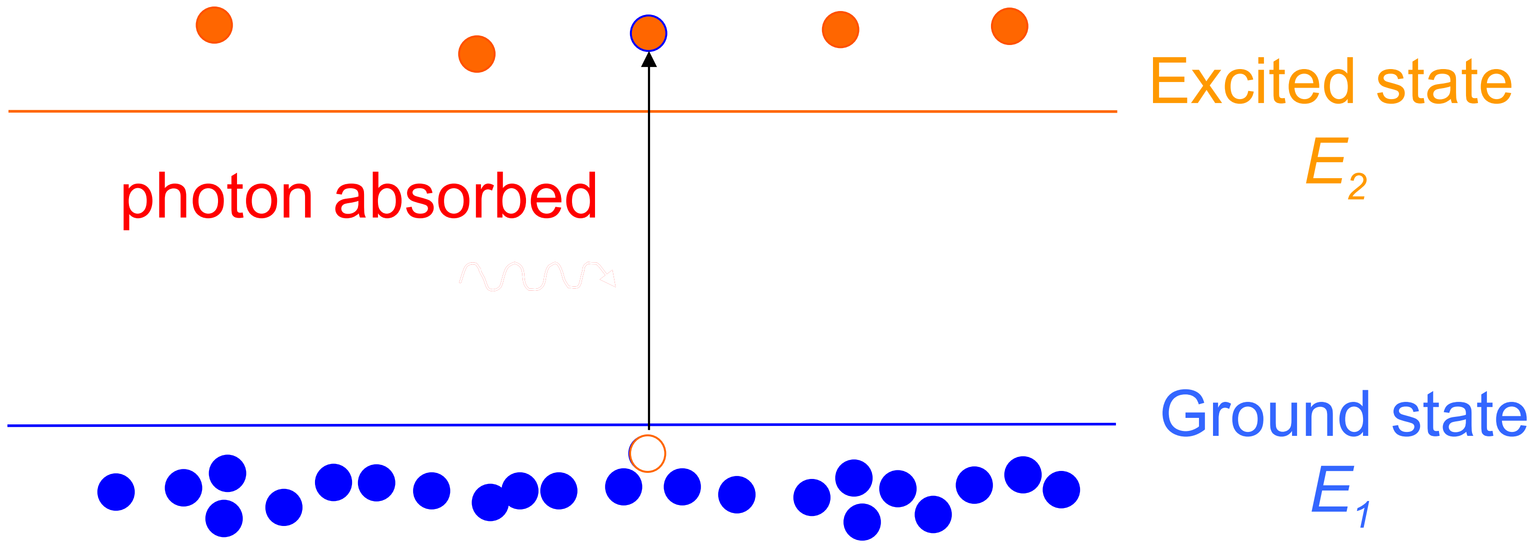
3.2 How do Lasers Produce Light?

- Electromagnetic fields induce transition between the different energy levels
- Three important optical transition processes will be discussed in some detail
  - Absorption
  - Spontaneous emission
  - Stimulated emission

3.2 How do Lasers Produce Light?

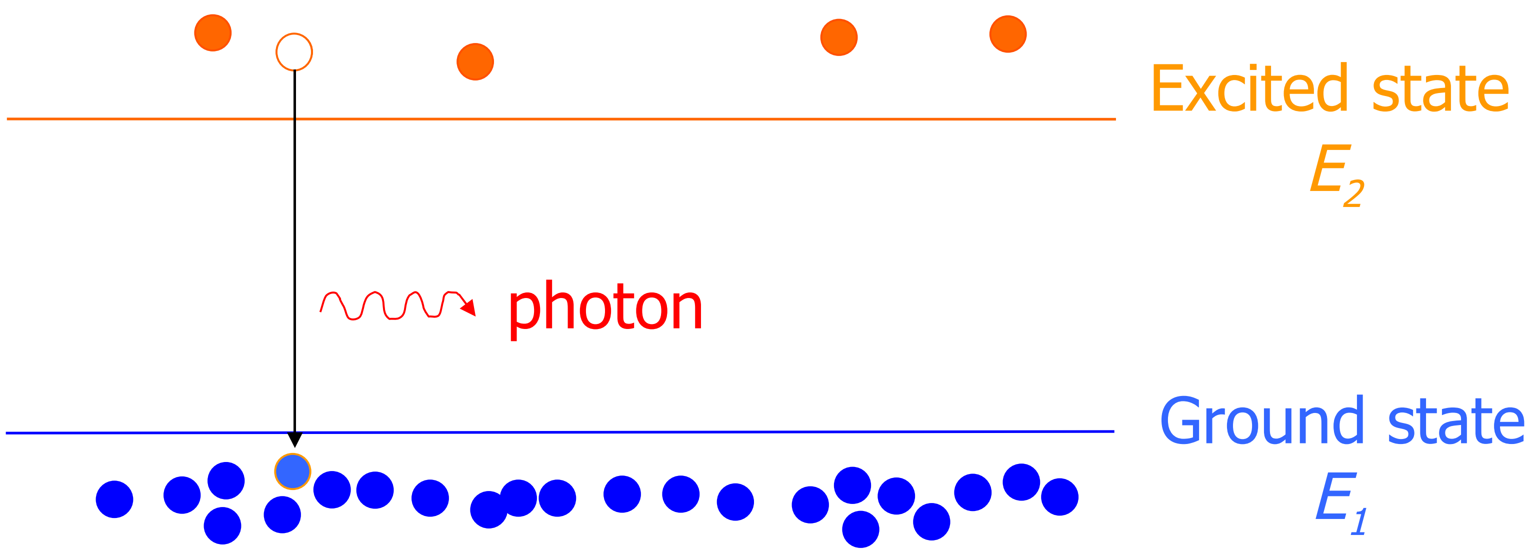
Absorption

- A photon with energy > (E2 – E1) can be absorbed by electron in ground state
- The electron subsequently jumps to excited state



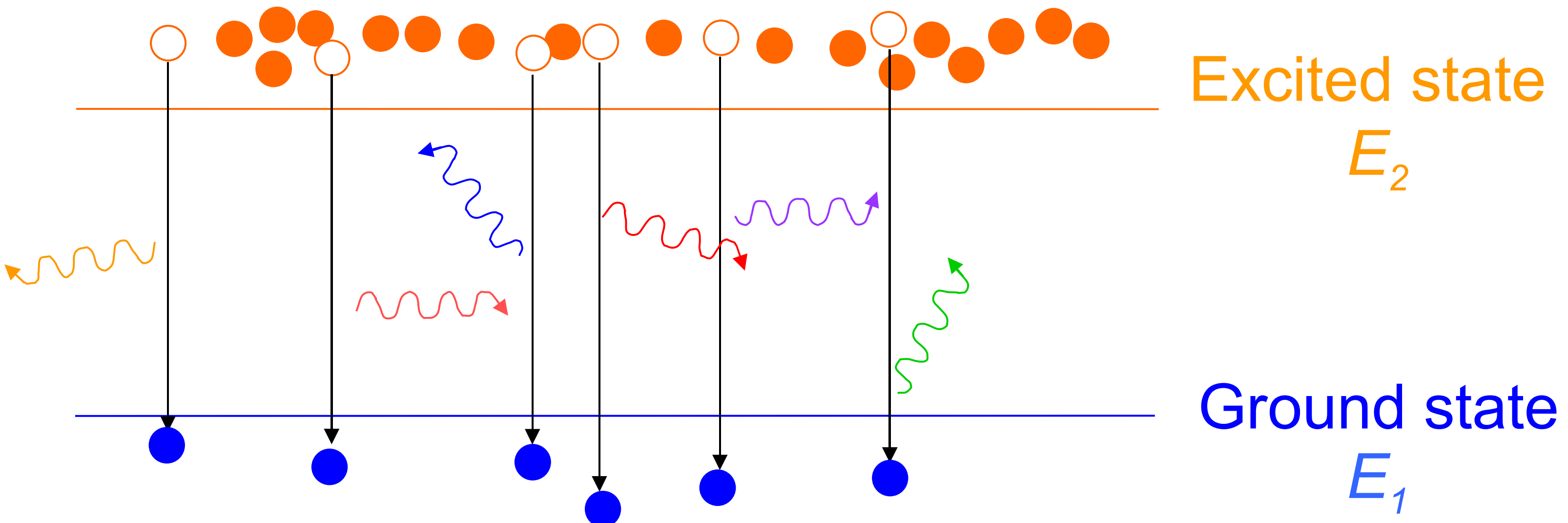
3.2 How do Lasers Produce Light?

- **Spontaneous Emission**: electron in excited state E_2 can spontaneously decay to state E_1
    - A photon with energy $hf > (E_2 - E_1)$ is emitted, where $h = 6.63 \times 10^{-34}$ Js (Planck's constant) and f is frequency



3.2 How do Lasers Produce Light?

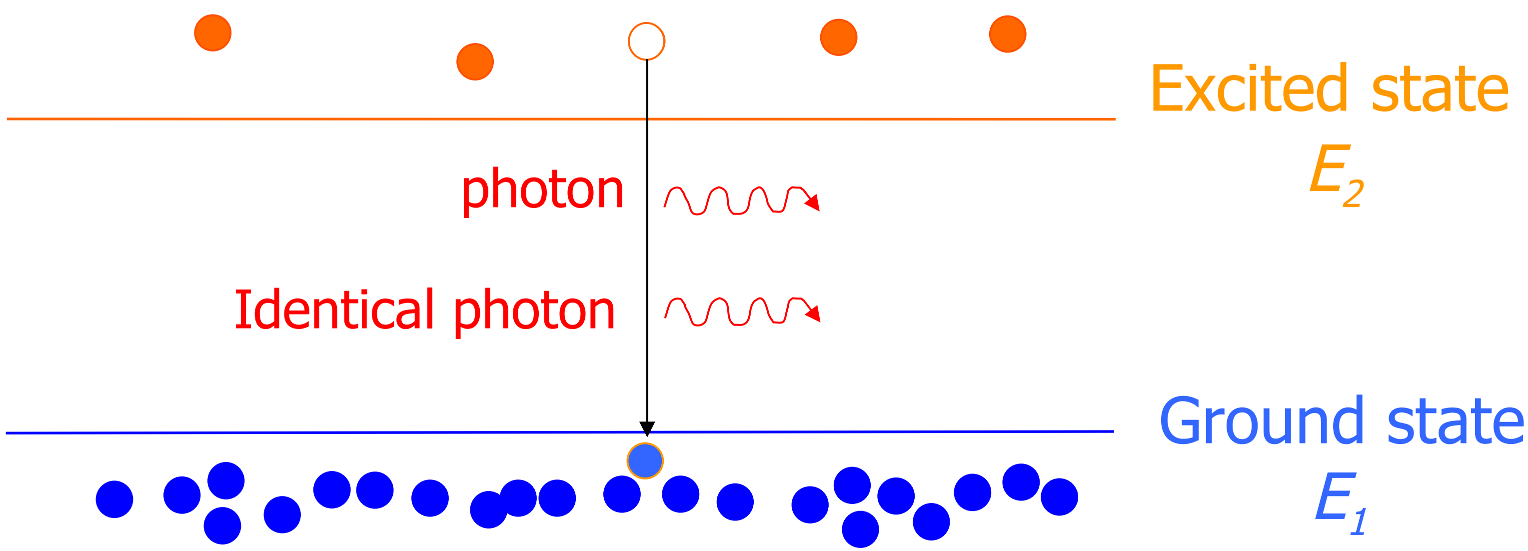
- Light produced by spontaneous emission is "noisy"
  - Random propagation direction, phase and frequency
  - Incoherent (broad spectral linewidth)
  - The effect used to produce light in LEDs



3.2 How do Lasers Produce Light?

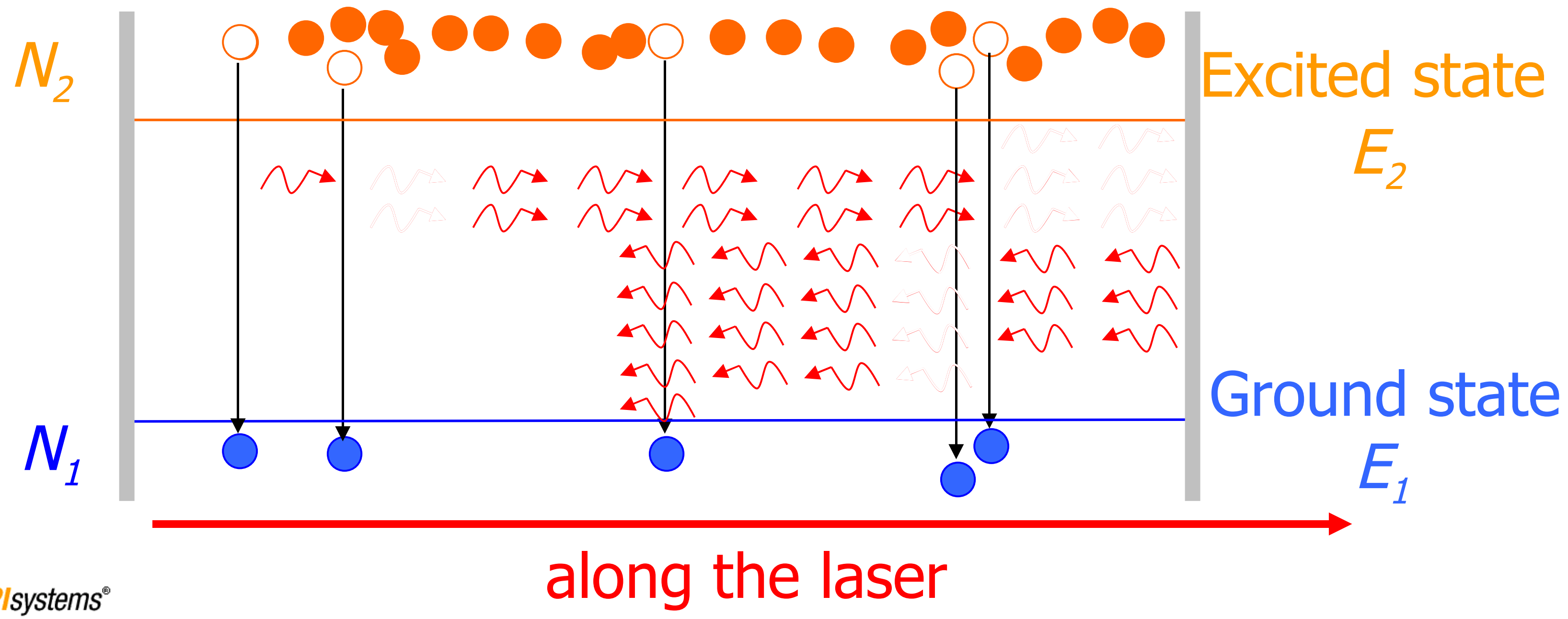
Stimulated Emission

- A photon with energy > ($E_2 - E_1$): triggers transition of an excited electron ⇒ identical photon is emitted
- Produced light is coherent (desirable)



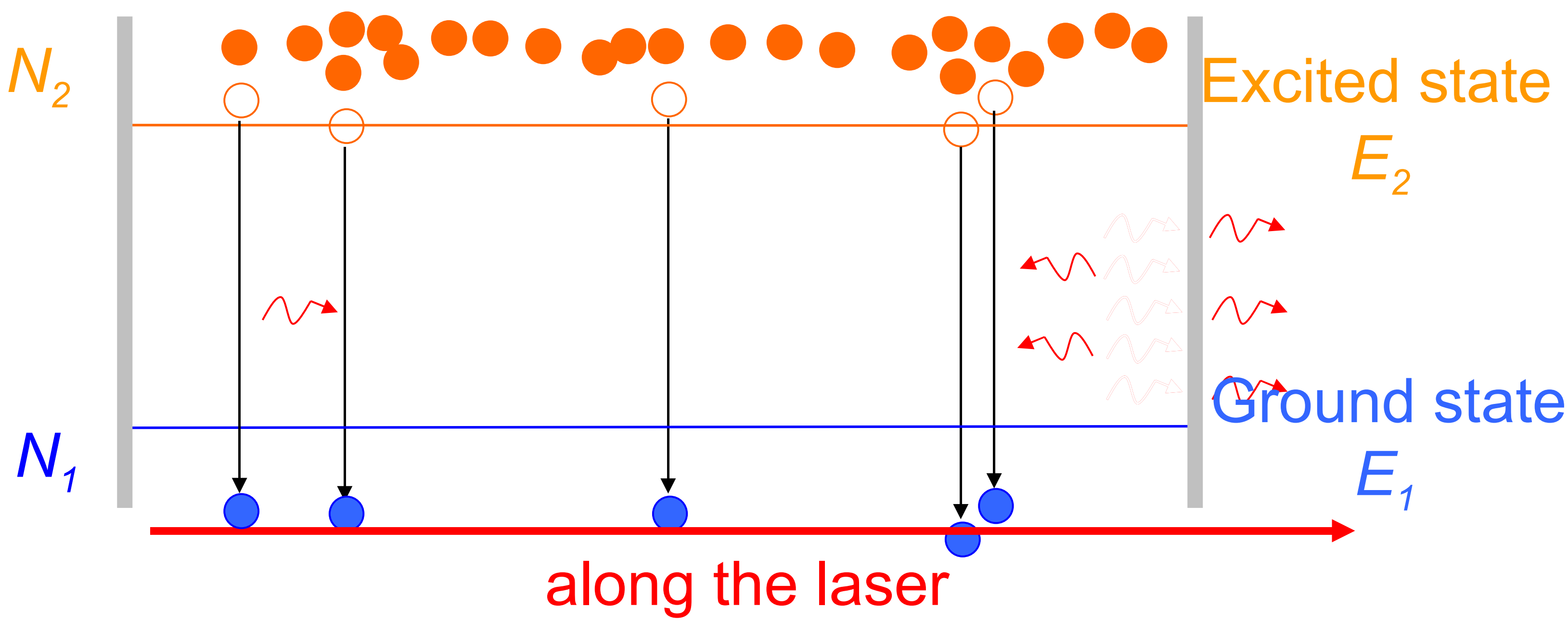
3.2 How do Lasers Produce Light?

- Light amplification by stimulated emission… is not strong, especially if the active region is short
  - Facets (mirrors) provide feedback into active region



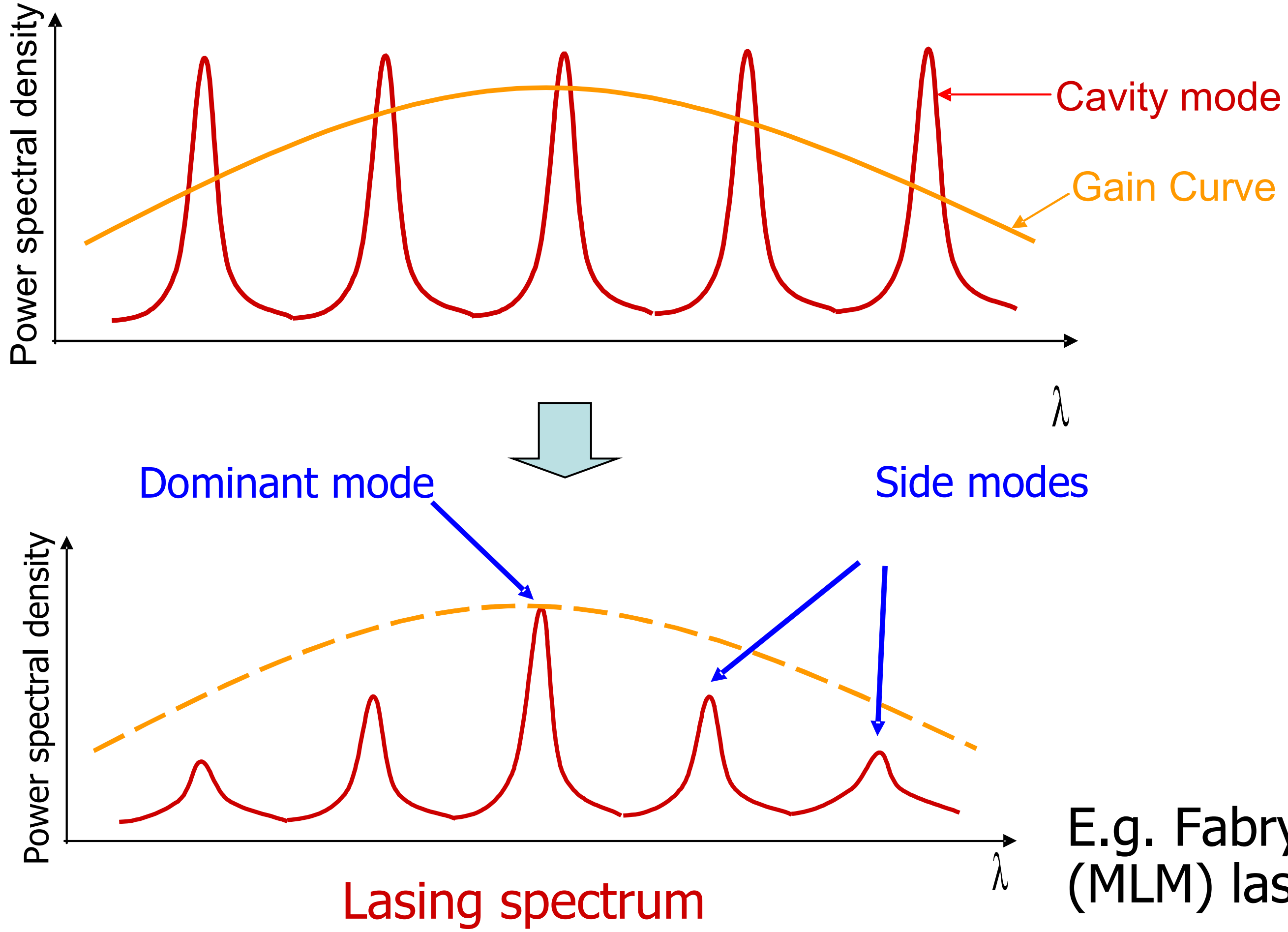
3.2 How do Lasers Produce Light?

- One facet is partially transmitting, to get output light waves with a resonant wavelength
  - Rest is reflected back repeatedly and amplified



3.2 How do Lasers Produce Light?

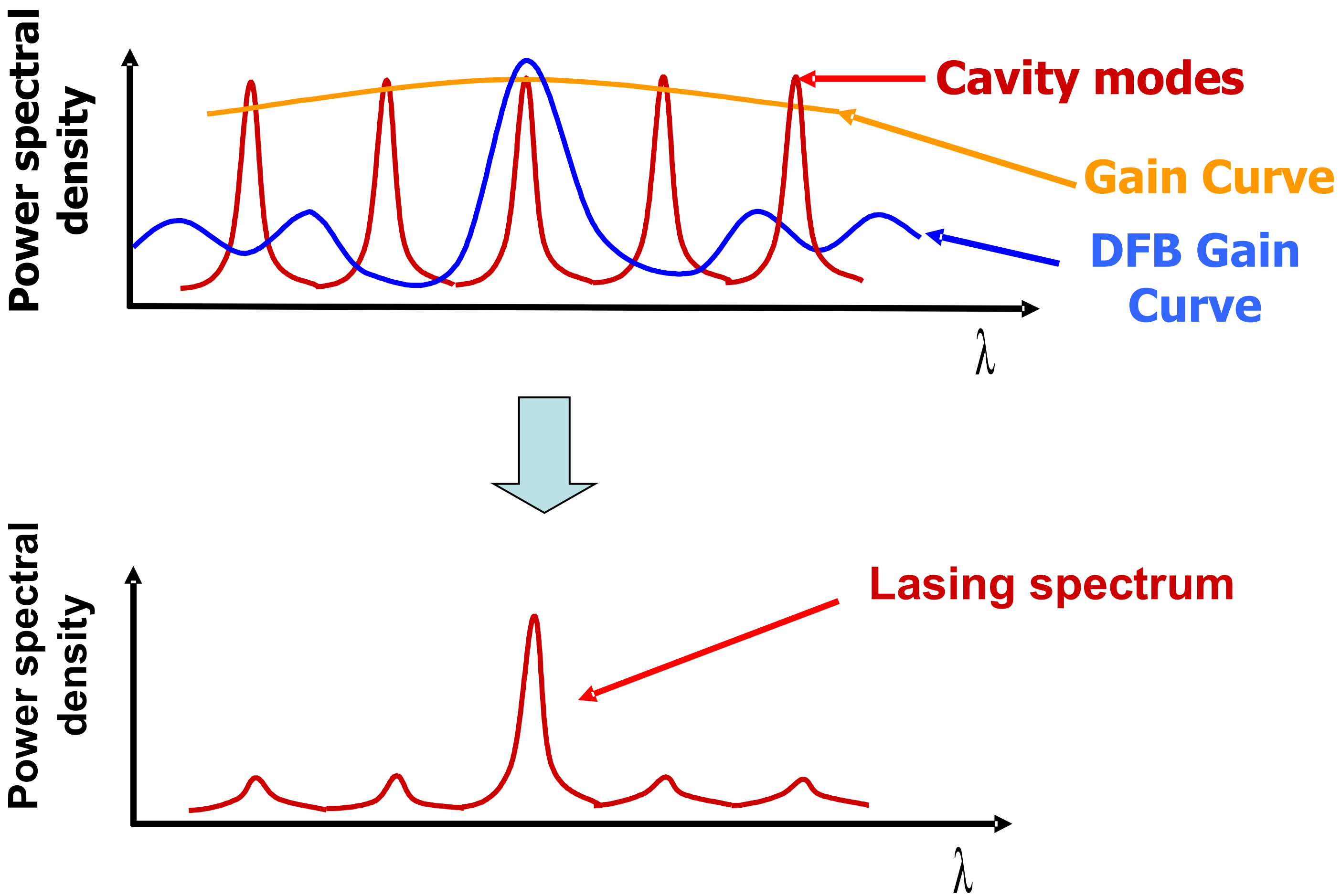
- Lasing action produces light waves at periodic wavelengths



E.g. Fabry-Perot (MLM) laser

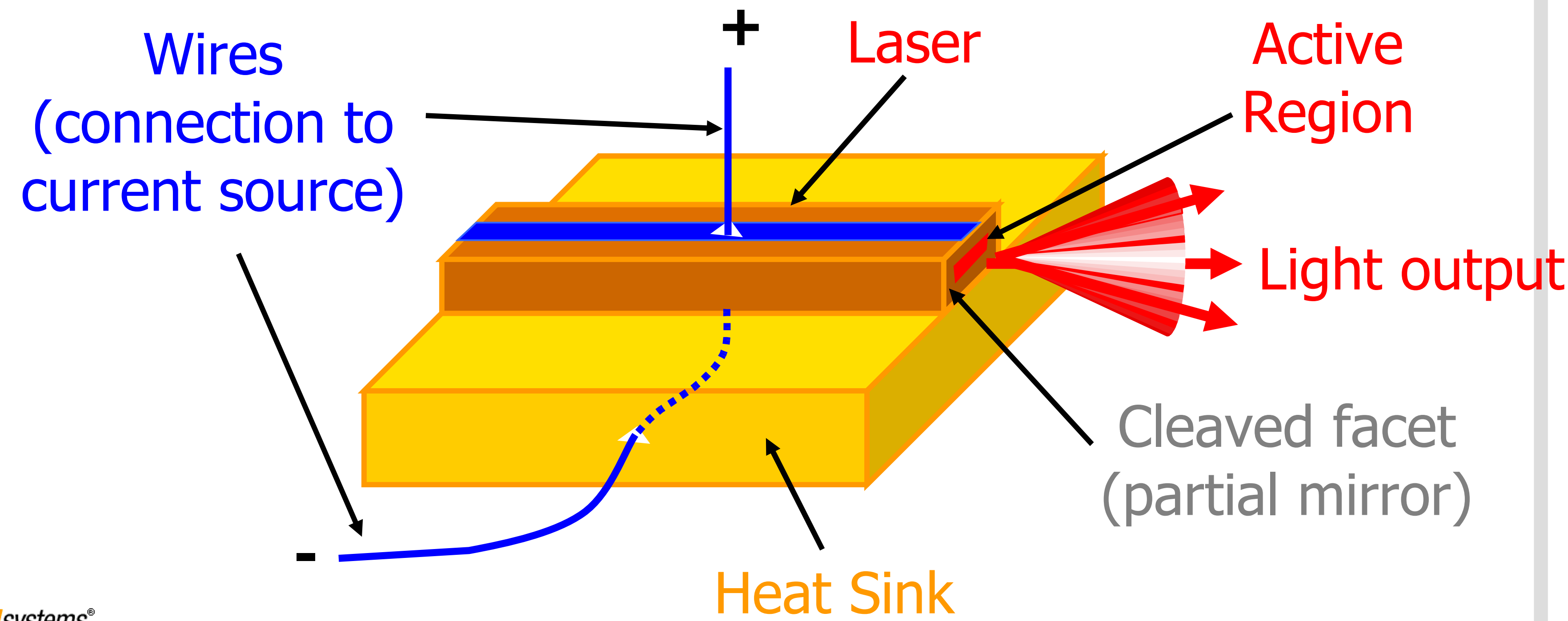
3.2 How do Lasers Produce Light?

- Distributed feedback (DFB) lasers ⇒ SLM laser



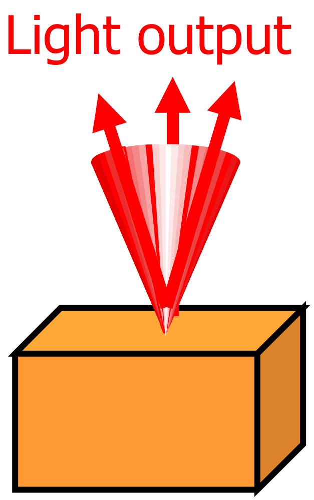
3.3 Structure of Lasers

- Fabry-Perot Laser (overhead view)
  - A type of an edge-emitting laser
  - 1550 nm window lasers are usually edge-emitting lasers

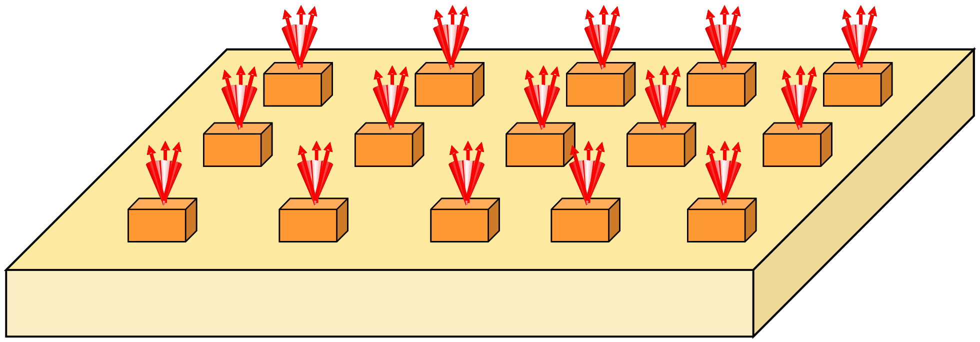


3.3 Structure of Lasers

- Now increased interest in surface-emitting lasers
  - Relatively easier packaging and testing
  - Easily integrated as 2D array on substrate wafer
  - Mostly used for 850 nm and 1300 nm transmitters in LANs



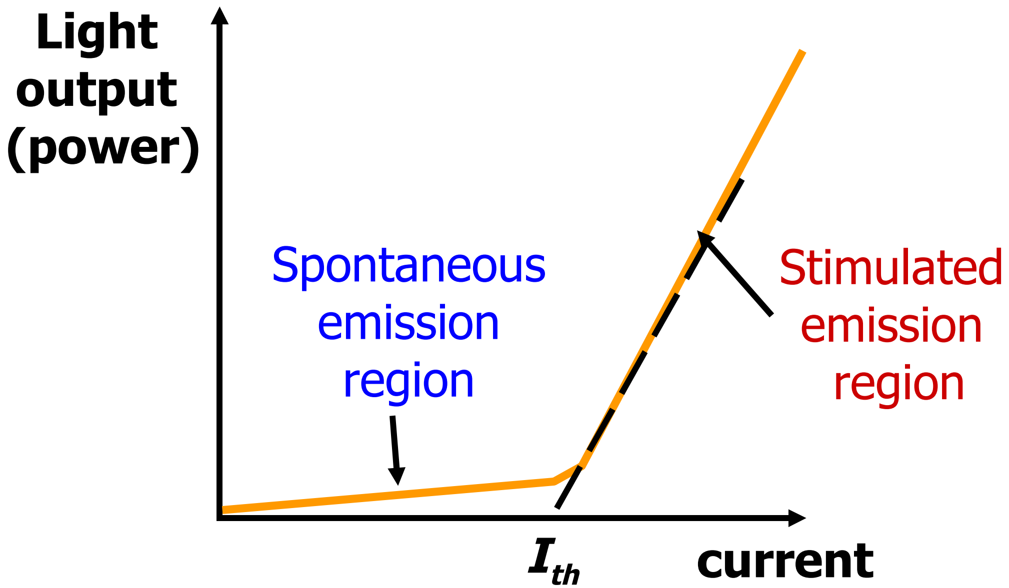
Surface-emitting laser



2D array of surface-emitting laser

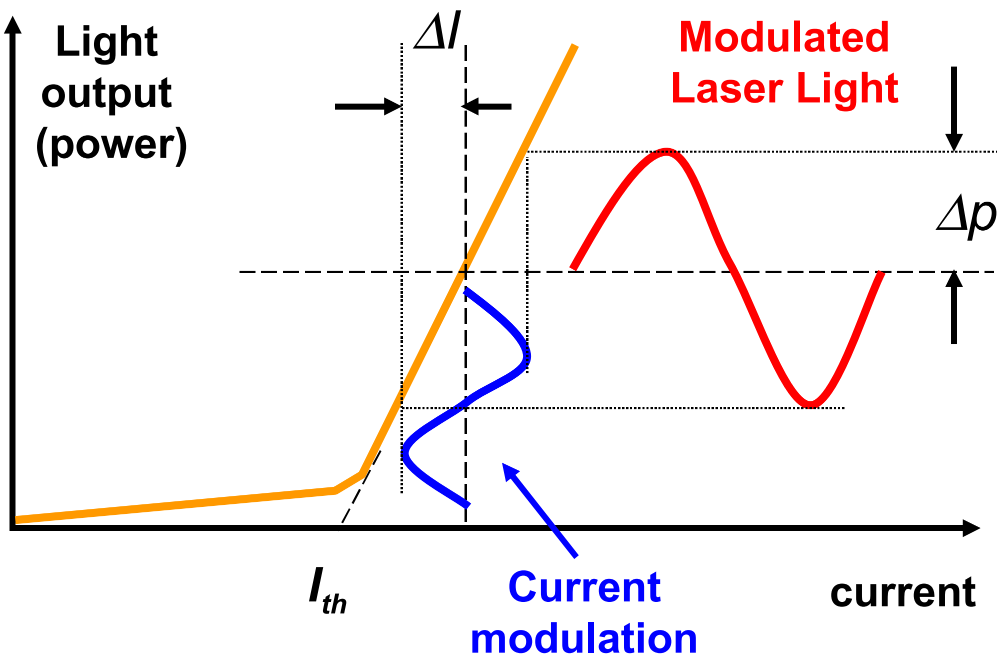
3.4 Characteristics of Lasers

- The *L-I* curve: output light power vs. input current
  - Below threshold current I_{th} laser acts like an LED
  - For $I > I_{th}$, light power increases linearly with I



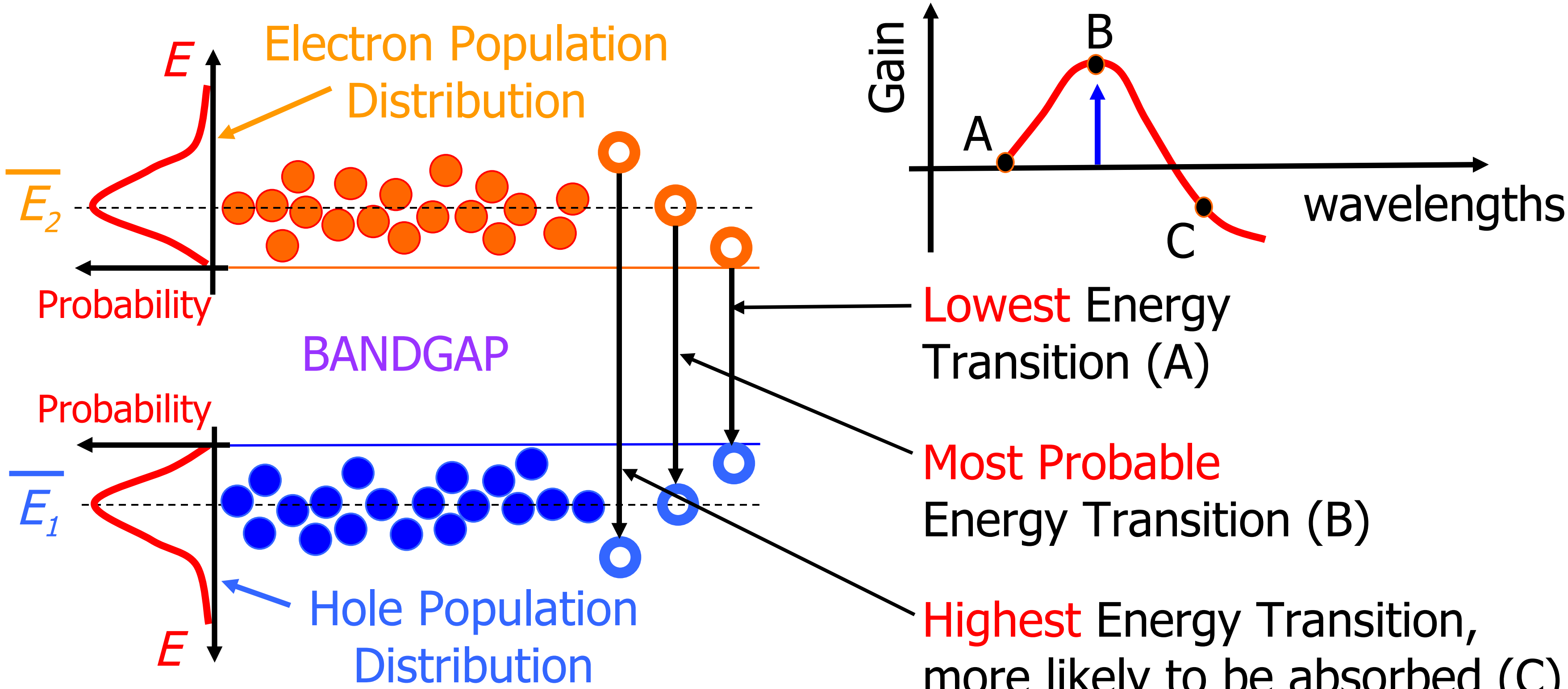
3.4 Characteristics of Lasers

❑The information is encoded on semiconductor lasers by current modulation



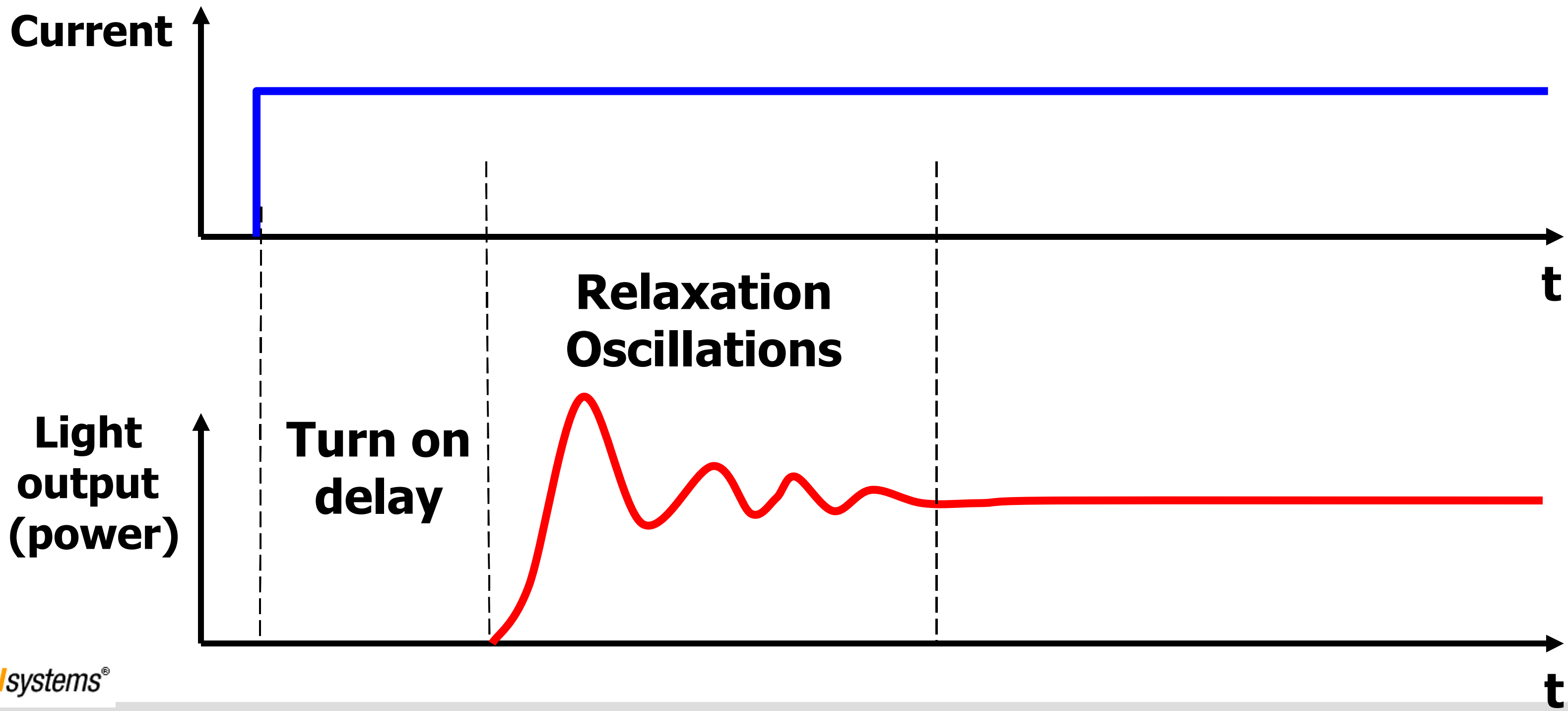
3.4 Characteristics of Lasers

- Lasers produce output at a range of wavelengths
  - All lasers have non-zero spectral linewidths
  - Due to distribution of E_2 and E_1 around mean values



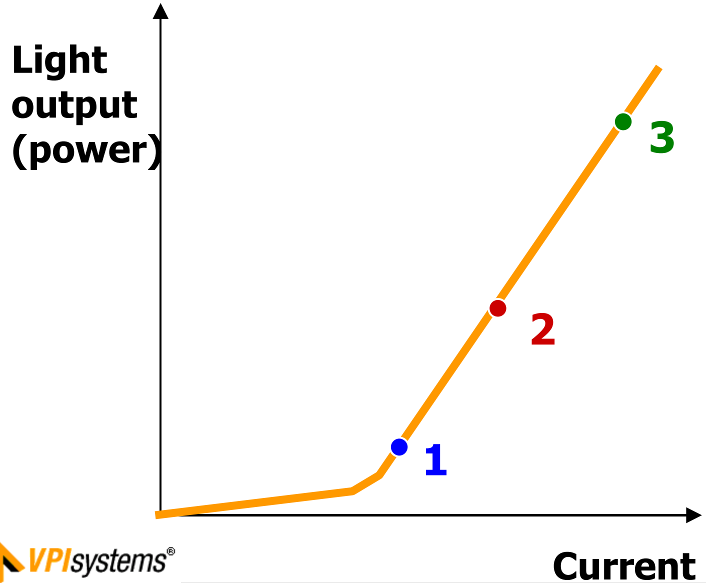
3.4 Characteristics of Lasers

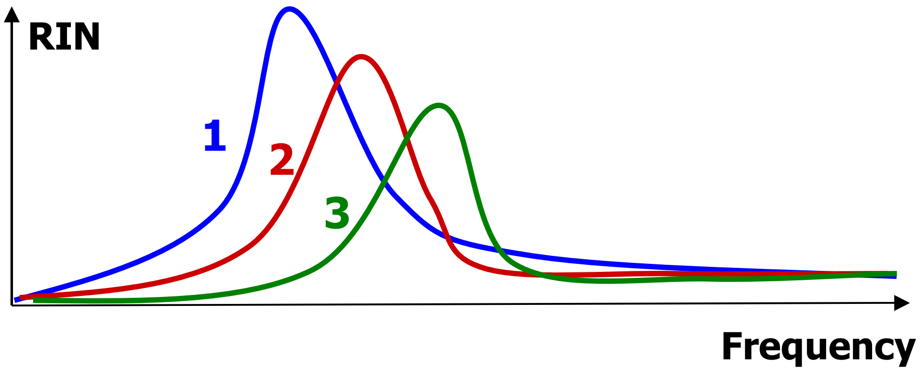
- Lasers have turn on delay between injection of current and generation of light
  - Stimulated emission only begins when carrier density is sufficiently high



3.4 Characteristics of Lasers

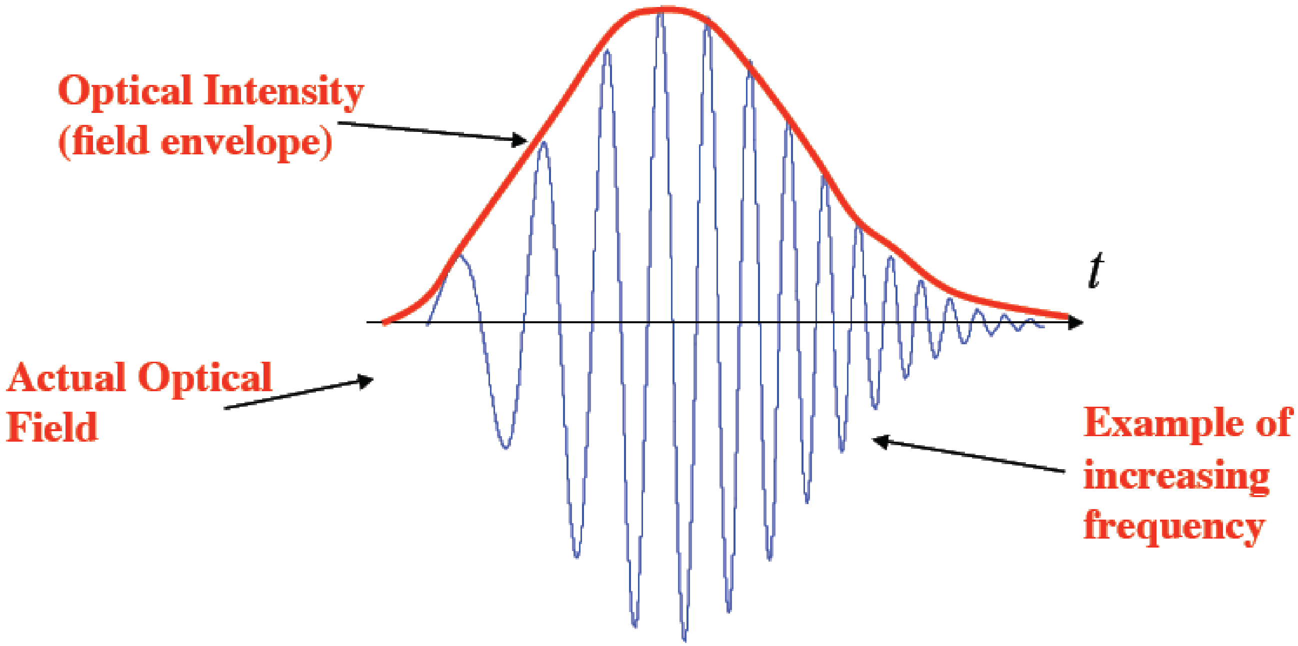
- Relative intensity noise (RIN)
  - Wavelength fluctuations due to laser ageing or temperature changes
  - Intensity fluctuations due to reflections from connectors and splices
  - Spectral shape of RIN depends on laser driving current level





3.4 Characteristics of Lasers

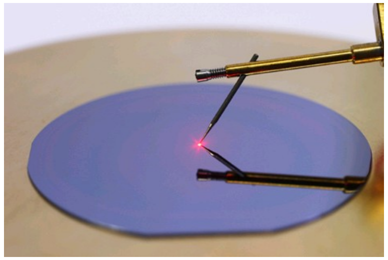
- Chirping of the laser output signal (pulses)
  - Instantaneous frequency fluctuations of output signal accompanying variation of drive current
  - Leads to broadening of spectral linewidth



3.5 Other Laser Types and Applications

- Solid state, fiber and gas lasers
  - Used in applications where high peak power and/or high continuous power is required

Laser printers



Semiconductor fabrication

Laser drilling/cutting

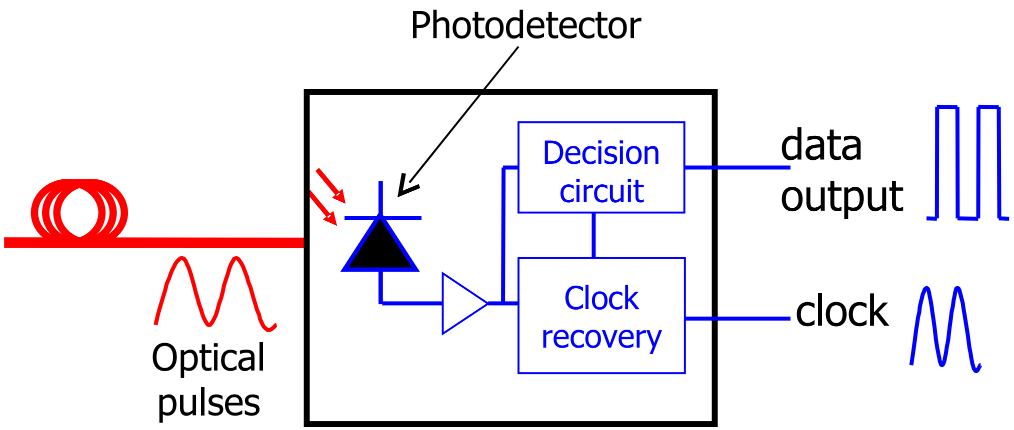
Air Force photo by Tech Sgt. Lance Cheung

Medical surgery

Laser light shows

4. Photodetector

- Convert an optical signal into an electrical signal
  - Photodetectors made of semiconductor materials absorb incident photons and produces electrons
  - If electric field imposed on photodector an electric current (photocurrent) is produced ⇒ photodiode



Optical Receiver

4. Photodetector

- Basic requirements of a photodetector
  - Sensitivity at the required wavelength
  - Efficient conversion of photons to electrons
  - Fast response to operate at high frequencies
  - Low noise for reduced errors
  - Sufficient area for efficient coupling to optical fiber
  - High reliability
  - Low cost

4.1 Types of Photodetectors

- Two main photodetectors used in optical communication systems
  - *pin* photodiodes
    - At best one electron generated when one photon absorbed
  - Avalanche photodiodes
    - The produced electron is induced a high electric field to knock off extra electrons ⇒ avalanche multiplication
    - More sensitive (can detect weaker signals)
    - More noisier and requires higher bias voltage
    - More sensitive to temperature and bias voltage variations
    - Costlier

4.2 Characteristics of Photodetectors

- Quantum efficiency (η) $\Rightarrow$ probability that an incident photon will produce an electron

$$\eta = \frac{\text{electrons per second}}{\text{photons per second}}$$

- Responsivity, R (A/W), $\Rightarrow$ photocurrent produced per unit of incident optical power

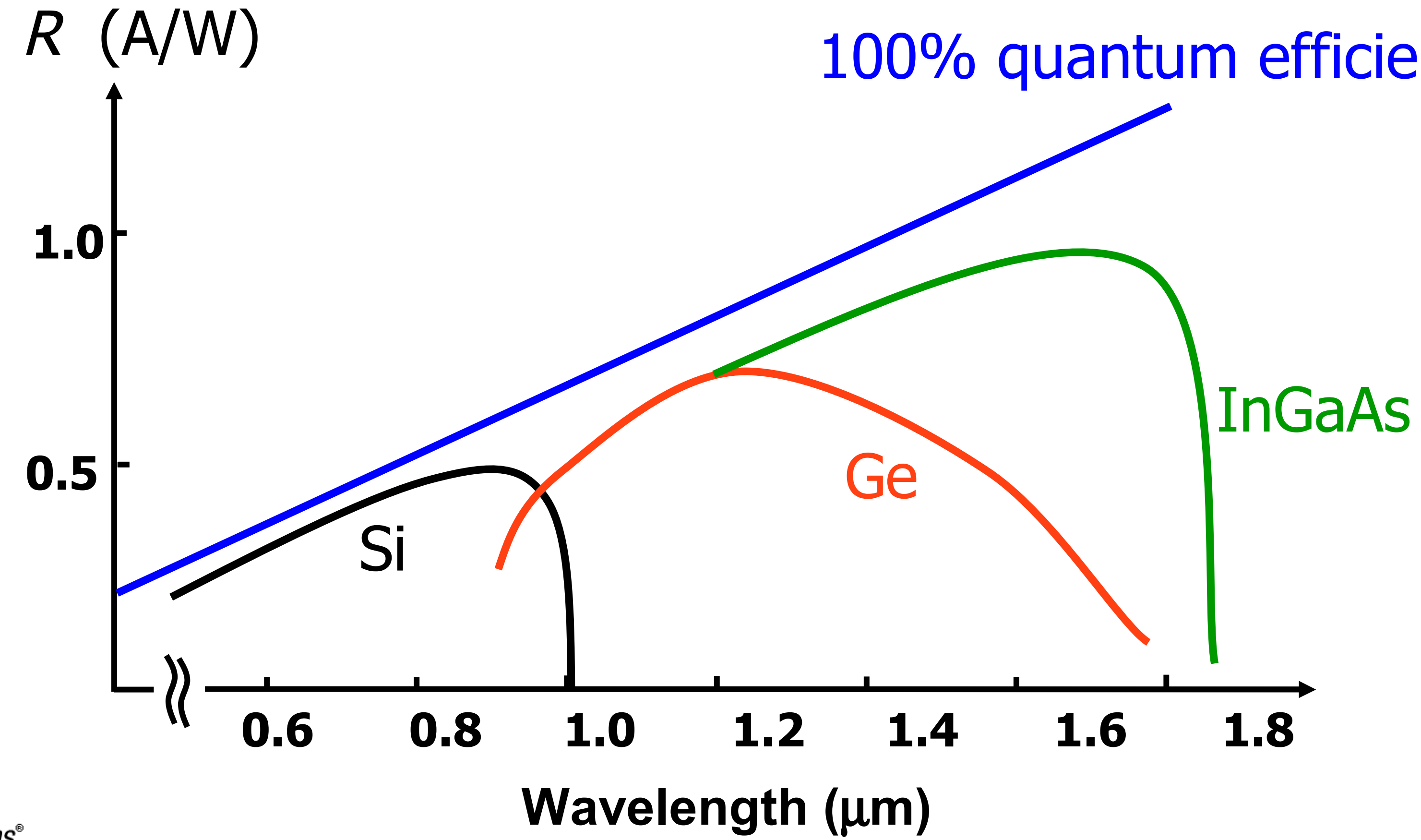
$$R = I_p / P_i = q\eta / hf \qquad \text{A/W}$$

with I_p = average photocurrent produced

P_i = incident optical power

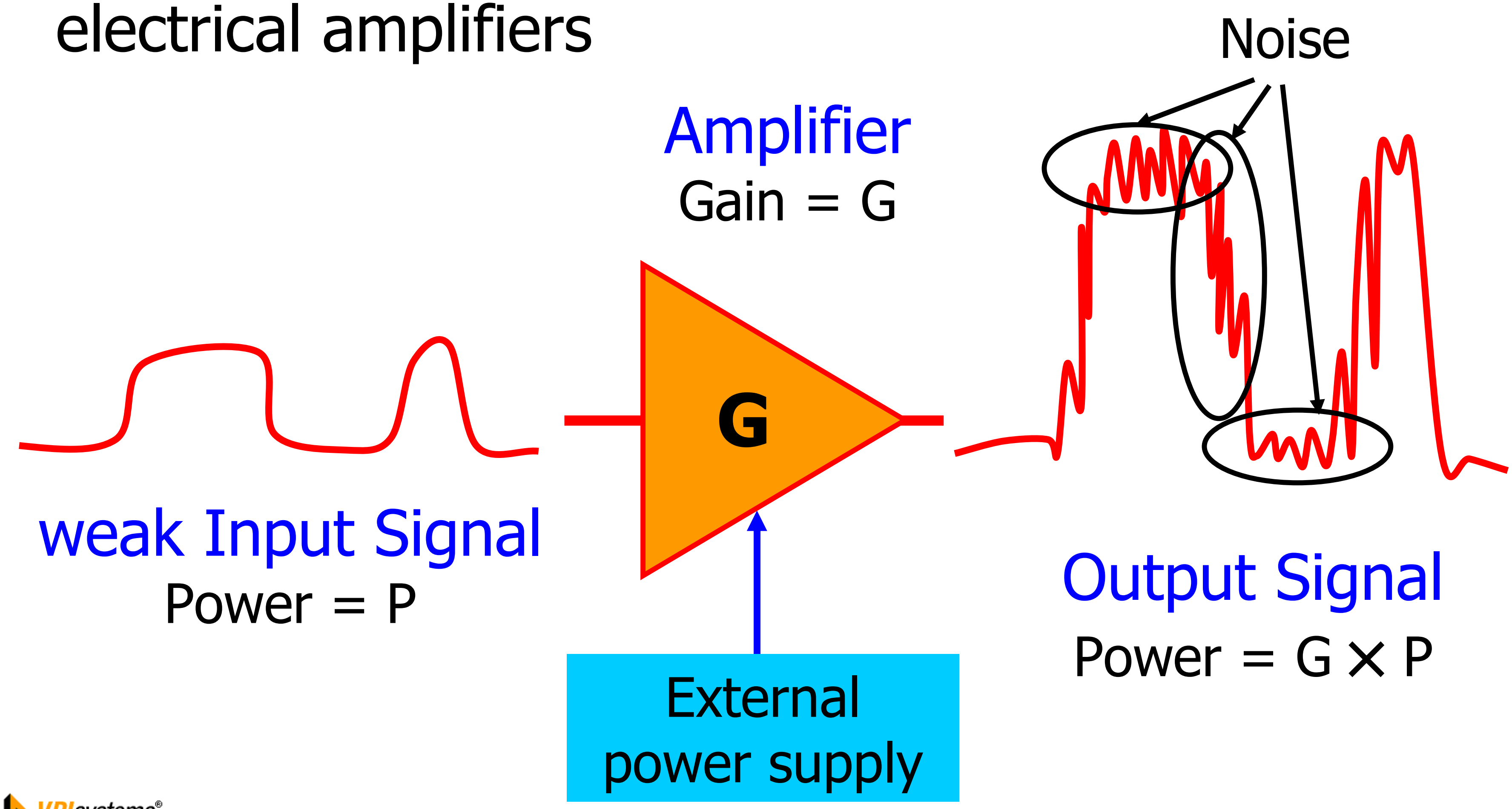
4.2 Characteristics of Photodetectors

- Different semiconductor materials suit different wavelengths
  - 850 nm (Si), 1300 nm (Ge) and 1550 nm (InGaAs)



5. Optical Amplifiers

- Optical amplifiers share some similarities with electrical amplifiers



5. Optical Amplifiers

- Similarities between optical and electrical amplifiers:
  - Signal amplification
  - Noise added to amplified signal
  - Gain and noise can be measured and calculated

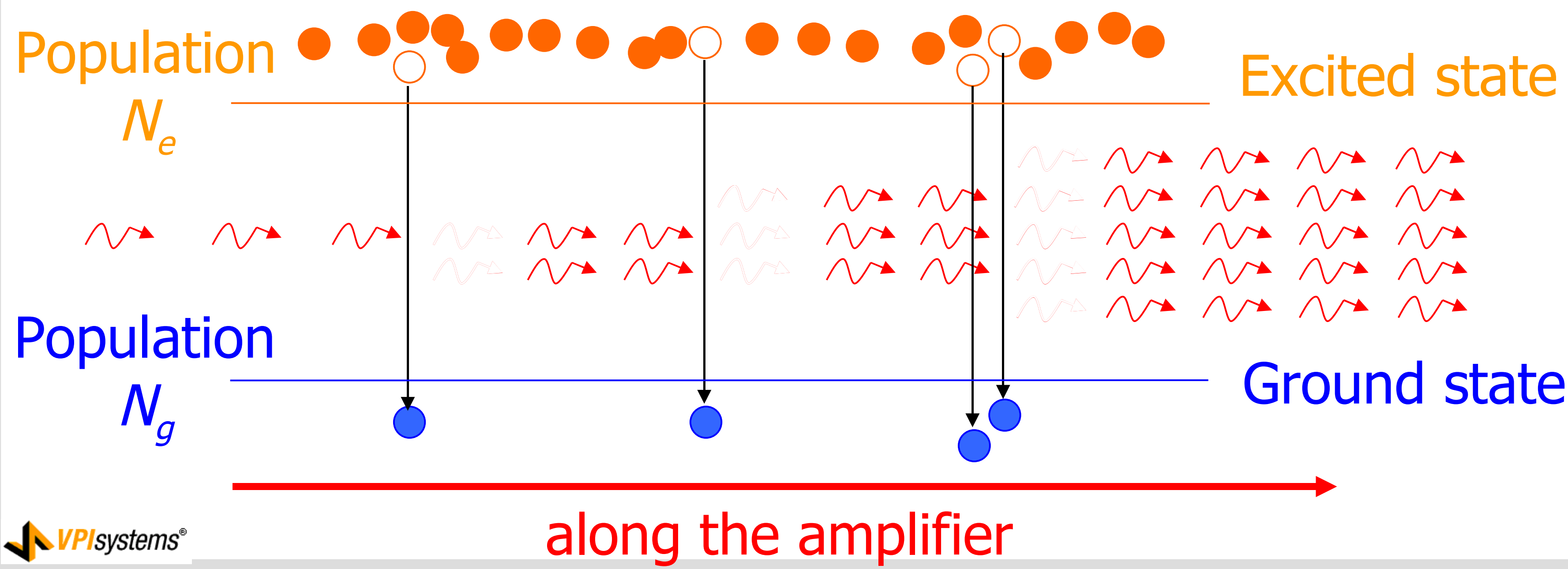
- Difference between optical and electrical amplifiers:
  - Large gain bandwidth

    3 THz — 25 THz (optical)

    2 GHz — 50 GHz (electrical)

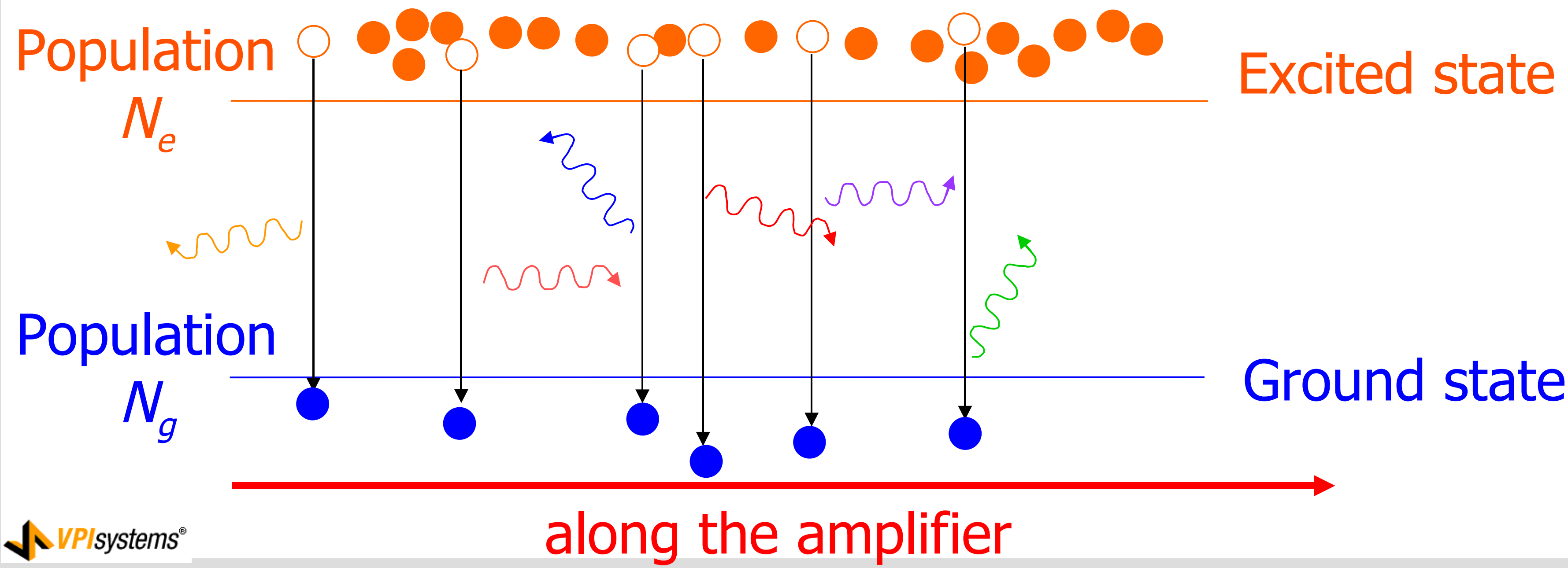
5.1 How do Amplifiers Work?

- Signal photon enters the amplifier
- It stimulates an ions to decay to ground state, which emits an identical photon
- This repeats... and the signal is amplified (Gain)



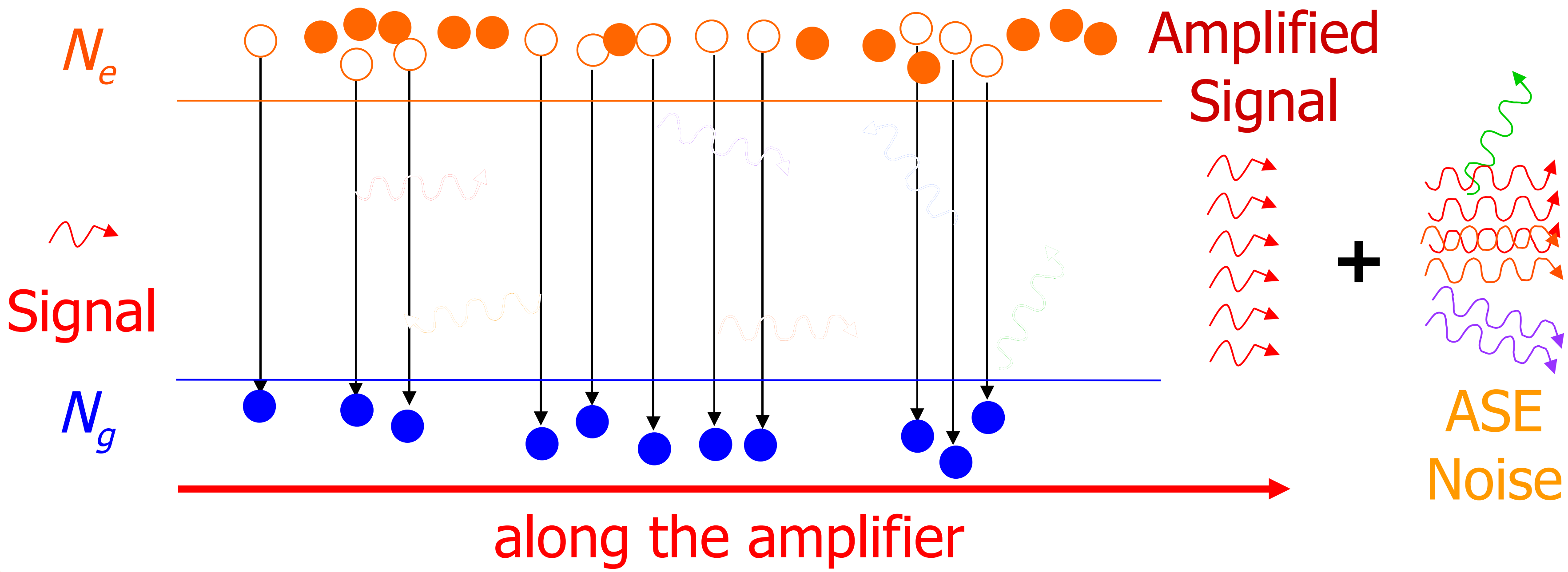
5.1 How do Amplifiers Work?

- Ions can decay to ground spontaneously
  - Photons emitted , random orientation, phase and λ
  - "Spontaneous Emission"



5.1 How do Amplifiers Work?

- A signal entering an optical amplifier will…
  emerge amplified…
  and is accompanied by amplified spontaneous emission (ASE) noise.



5.2 Optical Amplifier Performance

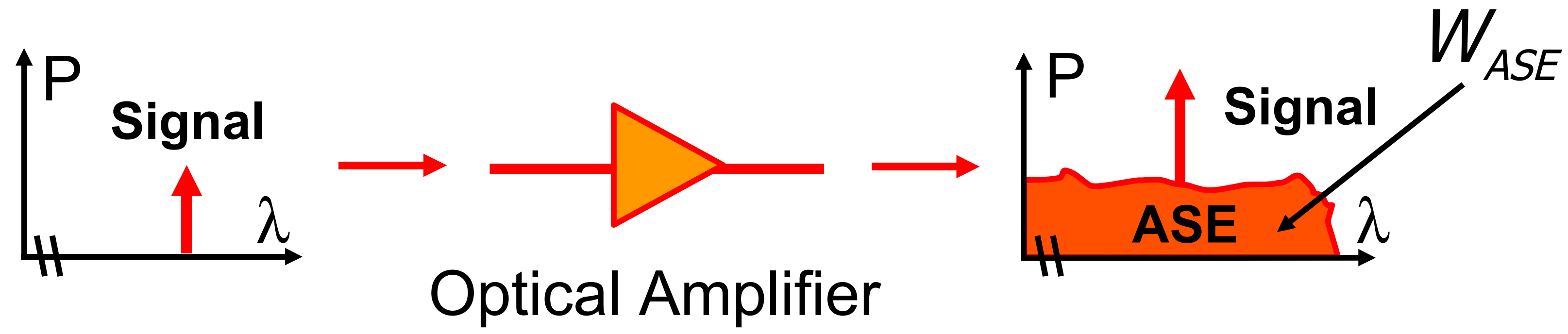
- Optical amplifier gain

$$G\ dB = 10\log_{10}\left(\frac{P_{signal\_out}}{P_{signal\_in}}\right) \quad dB$$

- Ratio of signal power at amplifier output to signal power at amplifier input
- Expressed in decibels (dB)

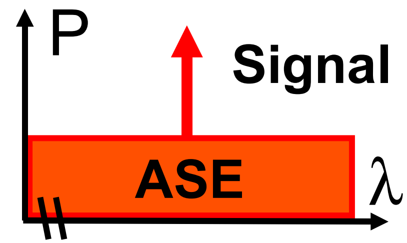
5.2 Optical Amplifier Performance

- An optical amplifier will produce ASE noise



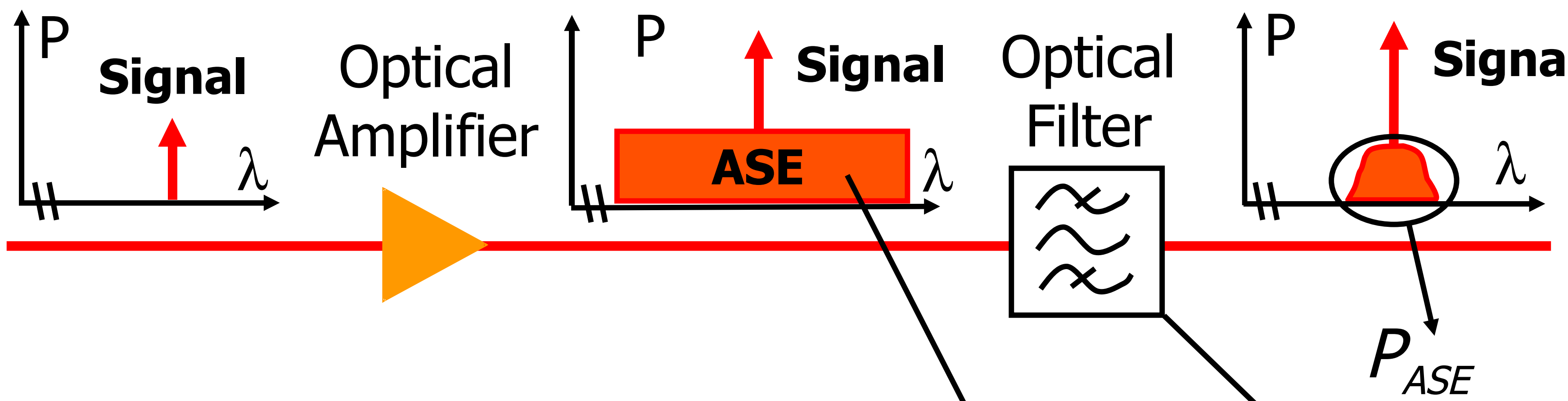
- W_{ASE} = ASE noise Power Spectral Density (PSD)

- W_{ASE} is approximately flat



5.2 Optical Amplifier Performance

- ASE noise is usually reduced by optical filtering



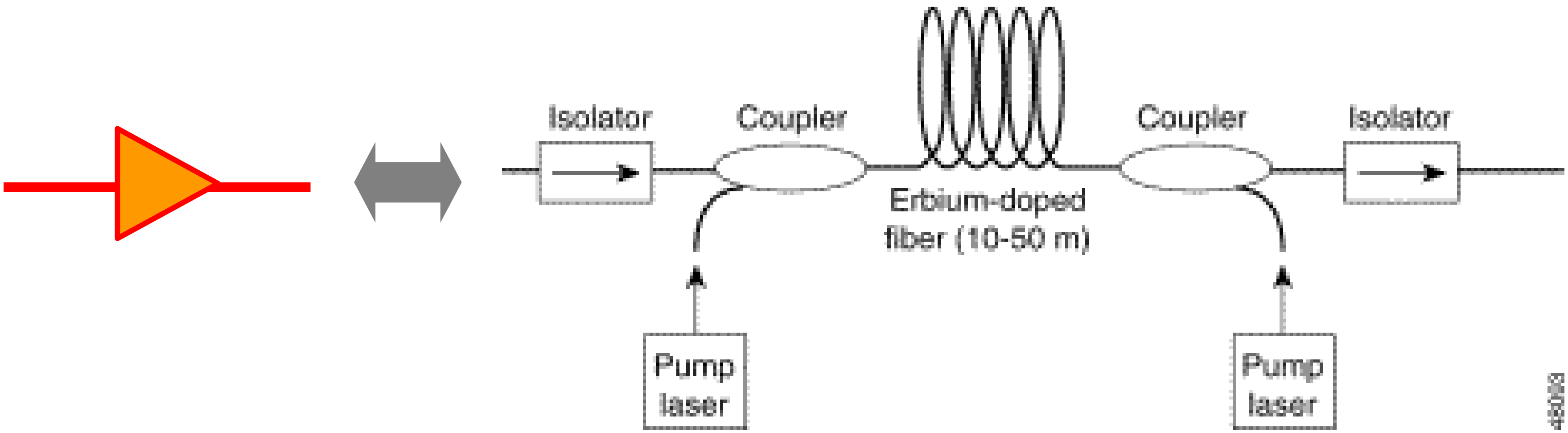
Average Noise Power :

$$P_{ASE} = W_{ASE} \times B_0$$

- B_0 is the optical filter bandwidth

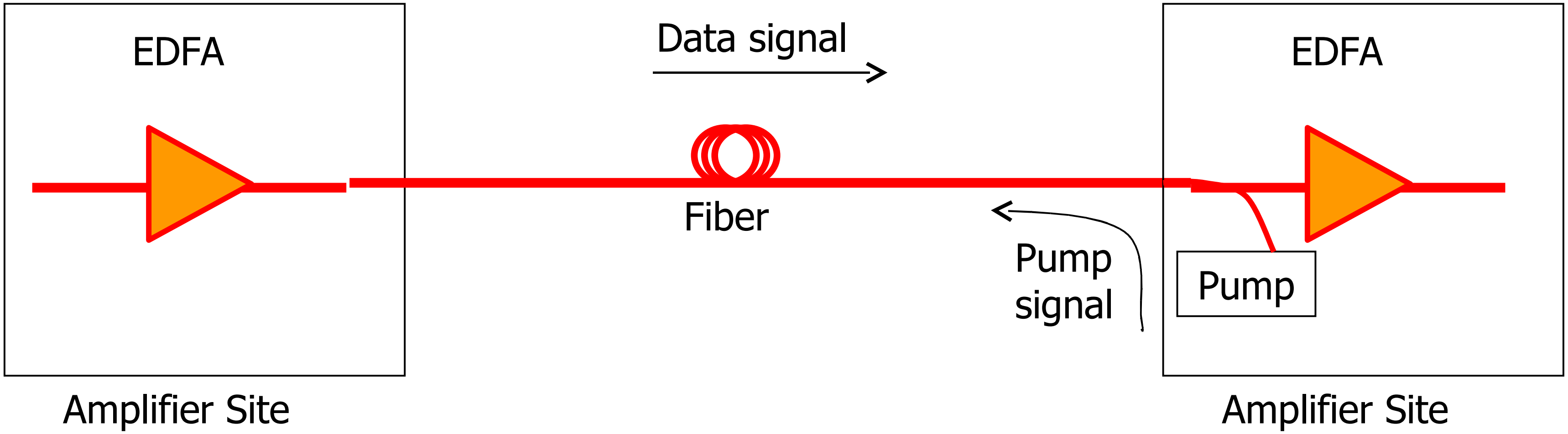
5.3 Types of Optical Amplifiers

- Erbium doped fiber amplifier (EDFA) most popular amplifier
  - Pump lasers output (980 or 1480 nm) coupled into the doped silica fiber forcing erbium (Er^{3+}) ions into exited state
  - Optical data bearing signals traverses doped fiber and stimulates Er^{3+} ions to ground state $\Rightarrow$ amplification
  - Amplifies ($G \cong 20$ dB) multiple data signals in C-band
  - Also amplifies L- band with some modifications



5.3 Types of Optical Amplifiers

- Raman fiber amplifiers (RFA)
  - Data signal amplified when in the transmission fiber itself
  - Employs a fiber nonlinear effect to transfer power from high-power pump signal to data signals
  - Can be tailored to provide gain in all wavelengths using multiple pumps
  - In practice used to complement EDFAs

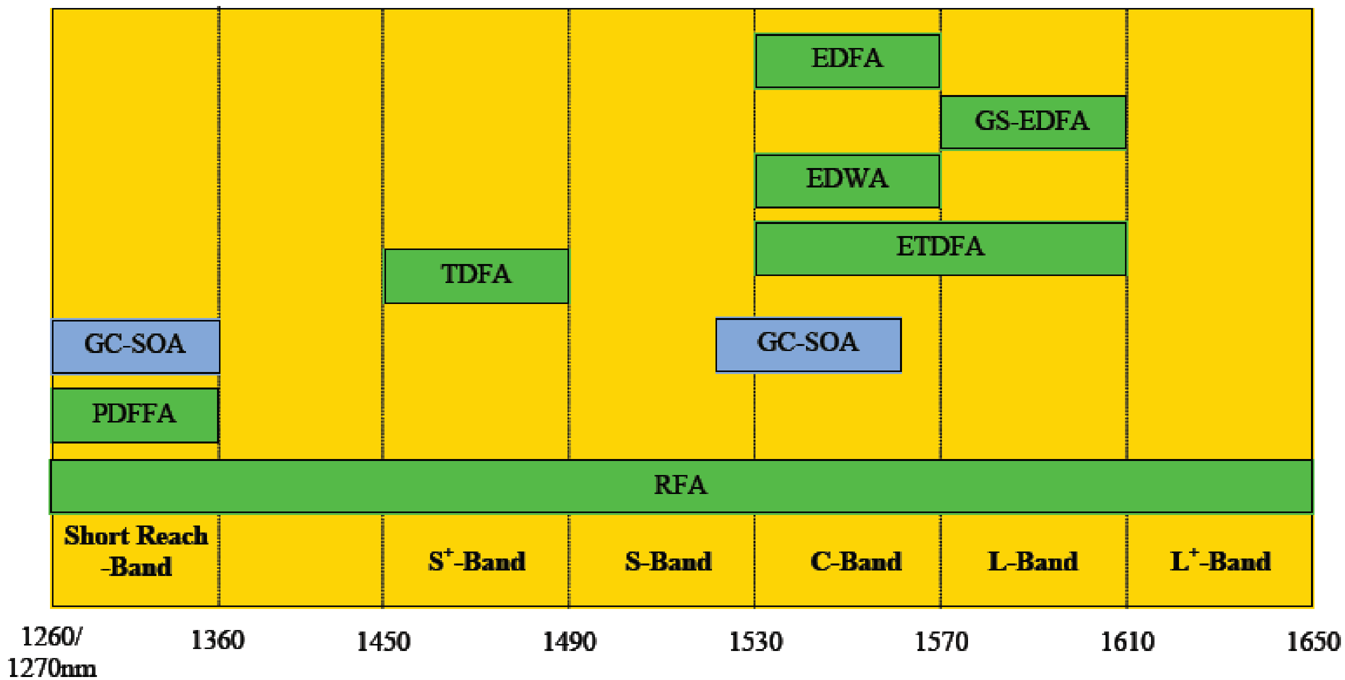


5.3 Types of Optical Amplifiers

- Semiconductor optical amplifiers (SOAs)
  - Like a semiconductor laser without mirrors
  - Advantages
    - Amplification bandwidths 30 to 100 nm
    - Can be integrated with other devices
  - Disadvantages
    - Introduces crosstalk in WDM systems ⇒ reduced by gain clamping
    - Higher input coupling losses ⇒ noise power more dominant
  - Used to construct other devices e.g. optical switches, wavelength converters

5.3 Types of Optical Amplifiers

- Various amplifies proposed for different bands



EDFA:	Erbium doped fiber amplifier (1530-1570 nm)
EDWA:	Erbium doped waveguide amplifier
ETDFA:	Telluride based erbium doped fiber amplifier (1532-1608nm)
TDFA:	Thulium doped fluoride based fiber amplifier
PDFFA:	Praseodymium-doped fluoride fiber amplifiers
GS-EDFA:	Gain shifted EDFA
GC-SOA:	Gain clamped semiconductor optical amplifier
RFA:	Raman fiber amplifier

Optically Pumped

Electrically Pumped

Source: D. Blumenthal, ECE228B lecture slides, USCB.

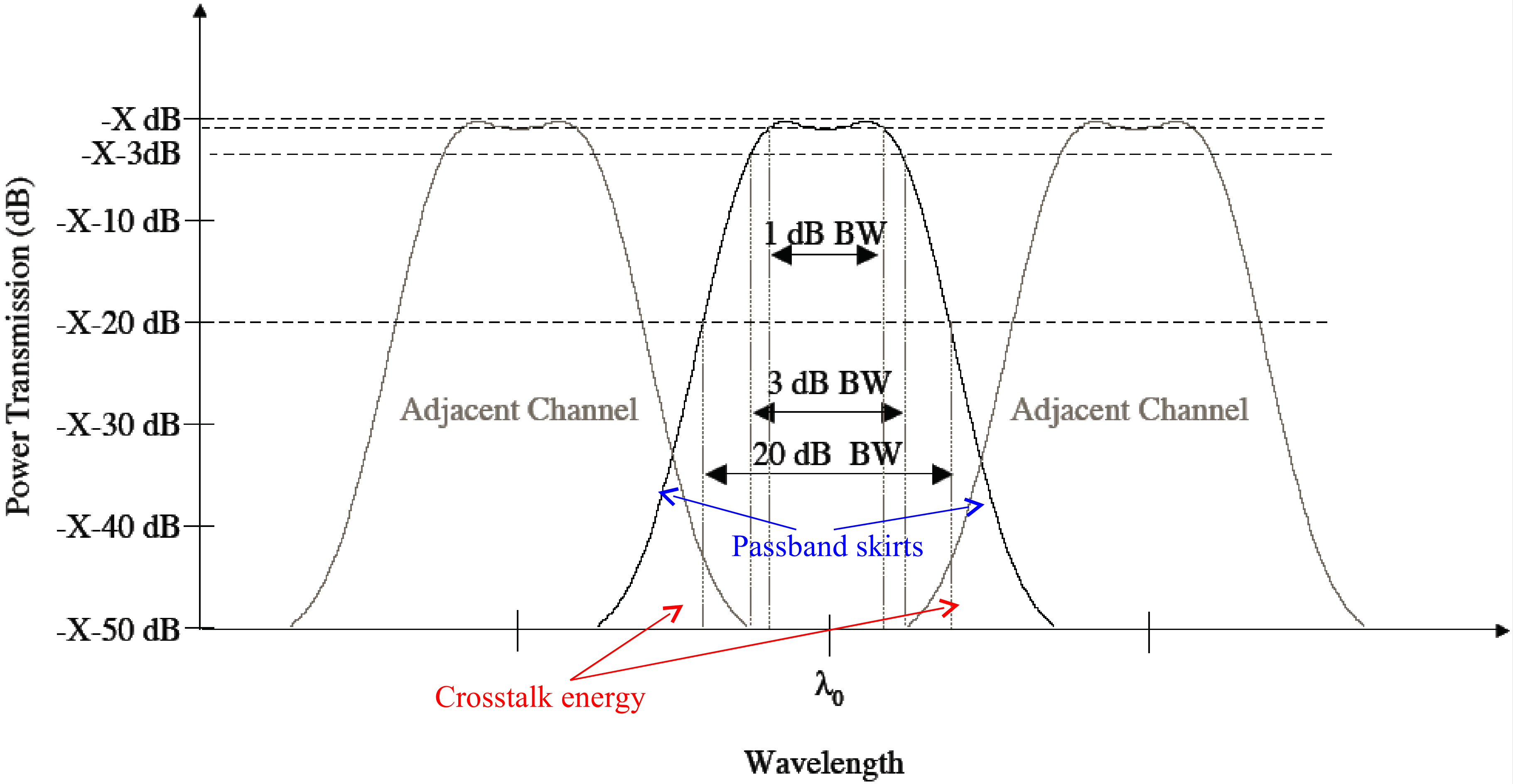
6. Optical Passive Devices

- Active devices
  - Devices which require power of some sort to function
    - e.g. optical amplifiers require electricity for pump lasers
  - Could also comprise processors, memory chips or other devices which are active
- Passive devices
  - Devices that merely pass or restrict light
  - Do not require powering ⇒ reduced cost and maintenance requirements
- Passive devices may become active if tunability is required

5.1 Optical Filters

- Optical filters have many uses in optical networks
  - Implementing multiplexers and demultiplexers in WDM systems
  - ASE noise filtering in links with optical amplification
  - Gain equalization of optical amplifiers
  - Spectral shaping or slicing of broad spectral linewidth optical sources

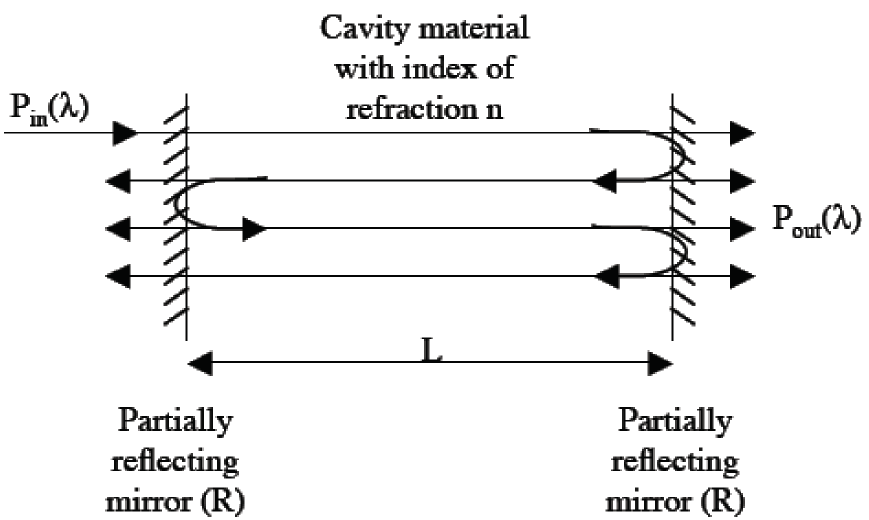
5.1 Optical Filters

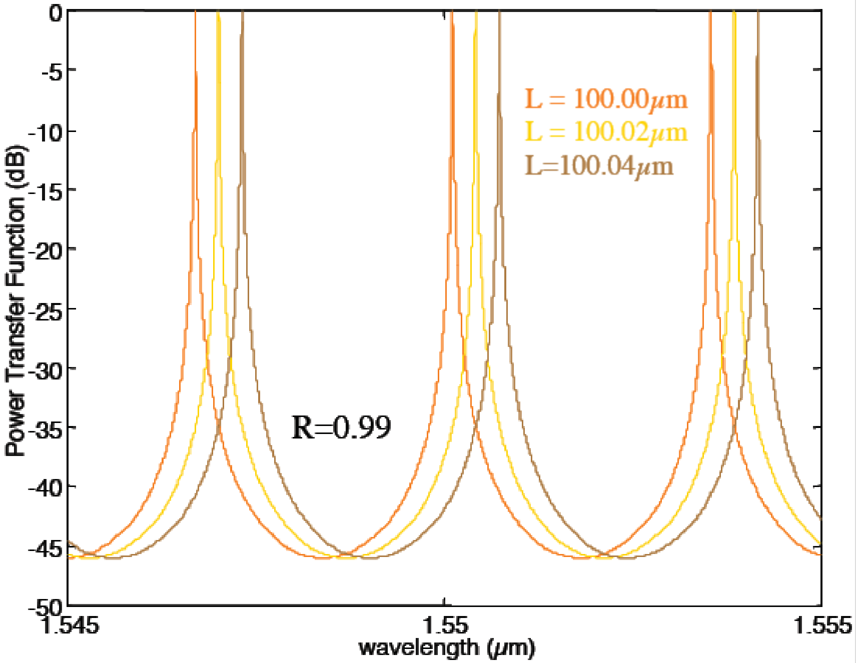


Important spectral-shape parameters of optical filters

5.1 Optical Filters

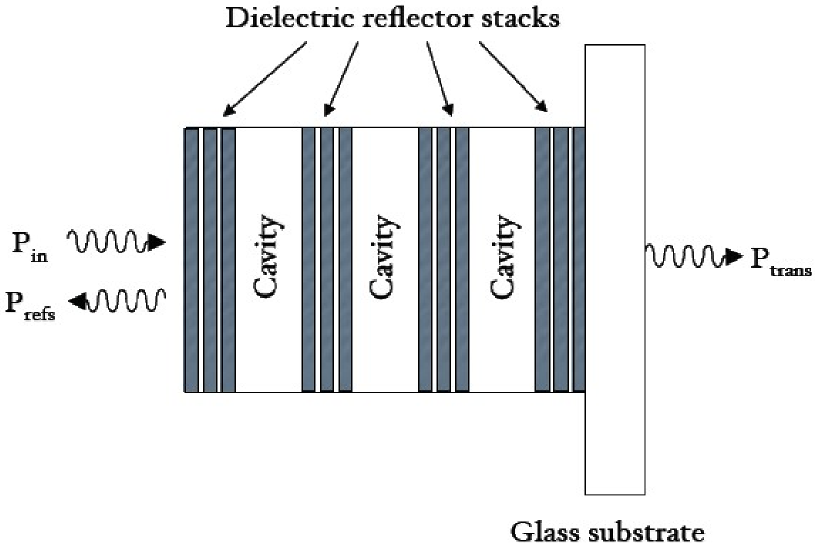
- Fabry-Poret filters
  - Has cavity formed by two partially reflective mirrors
  - Input enters 1st mirror and resonant wavelengths add in phase and leaves through 2nd mirror
  - Resonant wavelengths depends on cavity length *L* (tunable)
  - Filter bandwidth depends on mirror reflectivity *R*

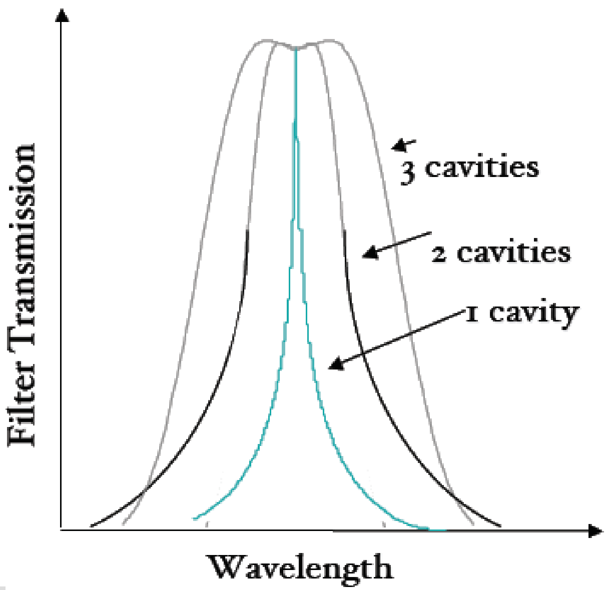




5.1 Optical Filters

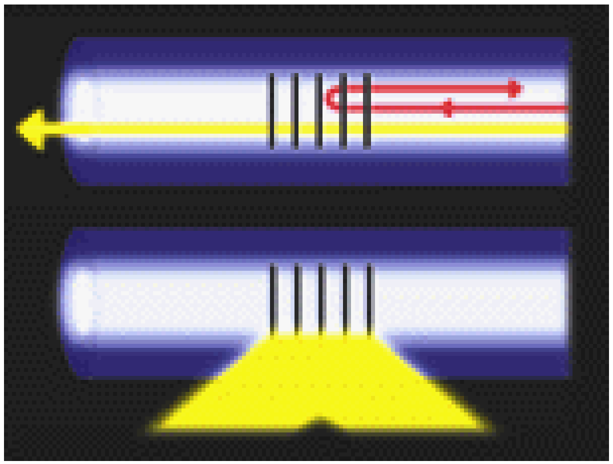
- Multilayer Dielectric thin film filters
  - Similar operation principle to Fabry-Perot filters
  - Multiple cavities realized by multiple reflective dielectric thin-film layers
  - The more the cavities the flatter the passband top and sharper the skirts



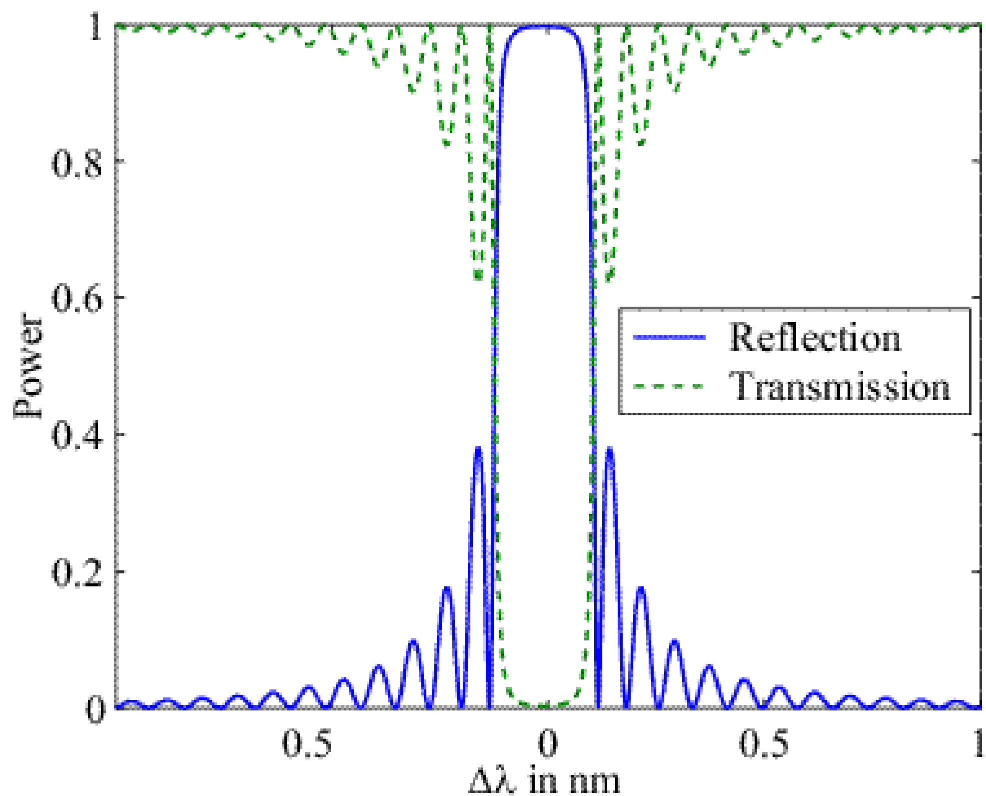


5.1 Optical Filters

❑ Fiber Bragg gratings

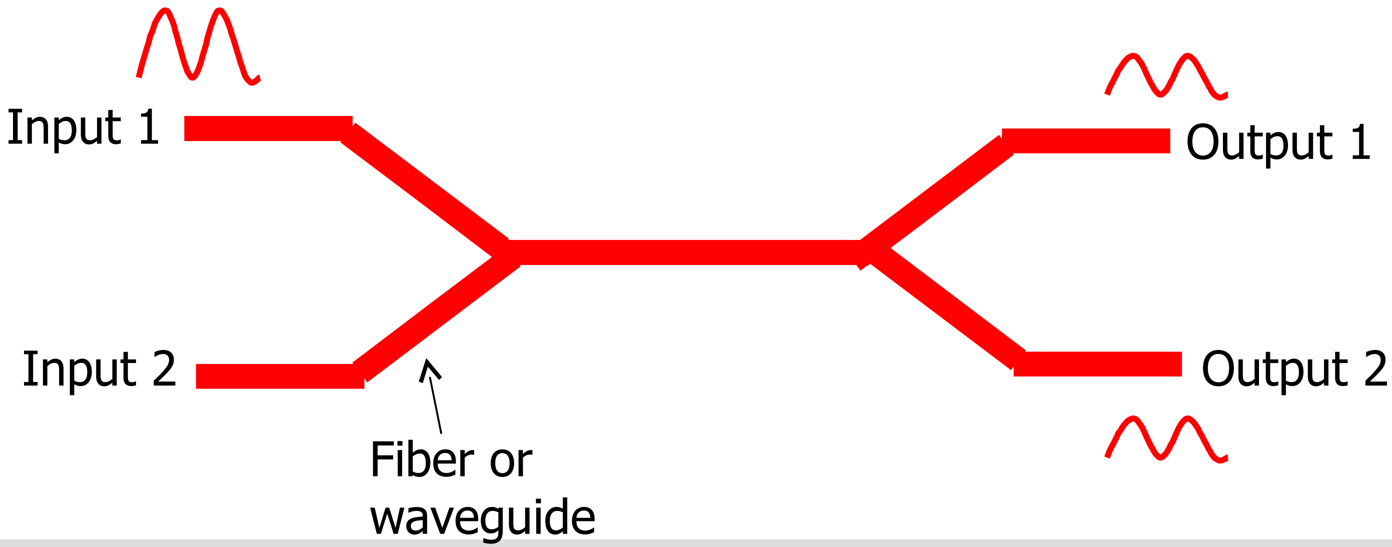


When the UV light passes through a phase mask, an interference pattern is produced creating a structural change in the core of the fiber resulting in a permanent and stable modification of its refractive index.



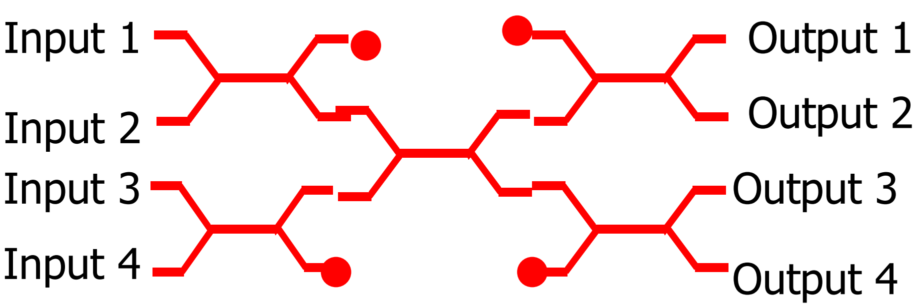
5.2 Couplers, Splitters and Combiners

- Directional (2×2) couplers
  - If input signal power distributed equally ⇒ 3dB coupler
  - Useful for combining and coupling signals e.g. in optical amplifiers
  - Also used for tapping off signal portions
    - e.g. 5/95 tap coupler with 5% tap ratio

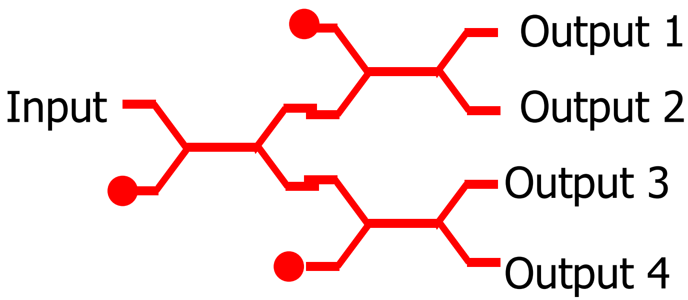


5.2 Couplers, Splitters and Combiners

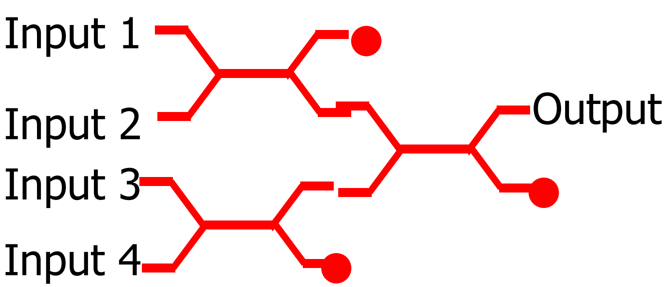
- Passive star couplers, combiners and splitters
  - Constructed by interconnecting multiple 3dB couplers
  - For signal broadcast or multicast



Example 4×4 star coupler



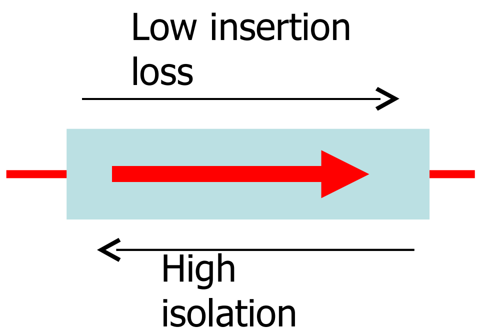
Example 1×4 splitter



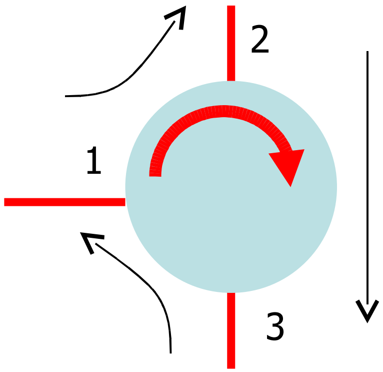
Example 4×1 combiner

5.3 Optical Isolators and Circulators

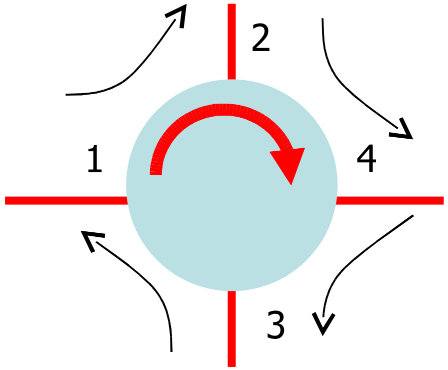
- Isolator ⇒ allow transmission only in one direction
  - Prevent reflections back into lasers, amplifiers etc.
- Circulators ⇒ isolators with multiple ports



Isolator



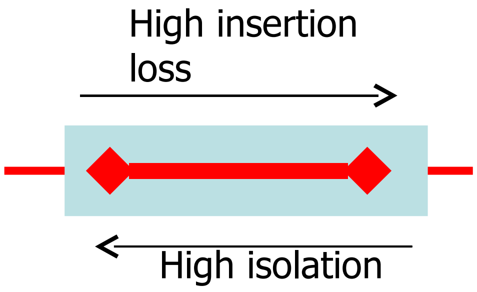
3 port circulator



4 port circulator

5.4 Attenuator

- Attenuator ⇒ restricts transmission in both directions



Attenuator

6. Conclusions

- Optical sources
  - Lasers very essential
  - Mechanisms, structure and characteristics
- Receivers
  - Photodiodes mechanisms and characteristics
- Optical amplification
  - EDFAs, RFA and semiconductor amplifiers
- Passive devices
  - Various filters types
  - Passive splitters/combiners, ssolators, circulators etc.
- Next lecture optical modulation and demodulation

Thank You!

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