Opto-electronic Transmitters

What is the Purpose of a Transmitter?

- The transmitter fulfils the function of optoelectronic conversion of the input electrical signal (data stream) into an optical signal suitable for transmission over the optical fibre communication channel.

- It may be separate from the optical fibre with launching optics interposed or may be permanently bonded to it in a so-called ‘pigtail’ configuration.

- The optical source is a semiconductor light emitting diode (LED) or semiconductor laser diode (SLD).

Desirable properties of the Optical Source

- Optical range: λ to match optimum for fibre, preferably 1.3 or 1.55μm
- Efficiency: Low electrical power device with high optoelectronic conversion efficiency.
- Channel coupling: Efficient coupling to fibre channel requires small emission area (to match small diameter of fibre core) and comparable numerical aperture.

Desirable properties of the Optical Source

- Modulation: ∞ bandwidth desirable. Realistically: direct modulation of optical output to $\approx$ 10Gbs-1 , external to $\approx$ 40Gbs-1
- Reliability: Long lifetime (mean time to failure).
- Construction: Compact and rugged, preferably solid state to integrate with other electronic systems.

Do Semiconductor Sources Meet Requirements?

Feature:	LED	SLD
• Wavelength range	λ = 0.8 -1.3µm available 0.8 - 0.9µm typical	0.6 - 1.6 available 1.3 & 1.55µm typ
• Spectral Width	$\Delta \lambda$:30→60nm	$\Delta \lambda$:0.5→5nm
• Coherence	Low	Medium/High

Do Semiconductor Sources Meet Requirements?

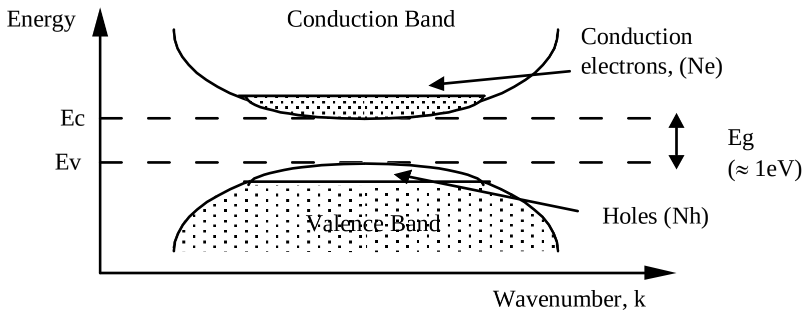
Feature:	LED	SLD
Efficiency:		
• Electrical Pin	V ≈ 1-2V, iop≈100mA	V ≈ 1-2V, iop≈100mA
• Optical Pout	10mW(max)	100mW(max)
Channel coupling:		
• Launch Efficiency	1→5%	30→50%
• Power Into Fibre	50µW(typ):100µW(max)	1→3mW(typ):10mW(max)
• Modulation bandwidth	50→100 MHz(typ) (200MHz(max))	1→3 GHz (typ) (10GHz(max))

Do Semiconductor Sources Meet Requirements?

Feature:	LED	SLD
Reliability:		
• Lifetime	Up to 10^7 hours	Up to 10^6 hours
Construction:		
• Complexity	Moderate	High (O/P power & temperature stabilisation)
• Cost	Few £s	Few £s $\rightarrow$ few £k
• Fibre Type	MMF	MMF/SMF
• BL	$\rightarrow$ 100Mbs-1 - km	$\rightarrow$ 100Gbs-1 - km
• Application:	LANS - Token Ring - Ethernet - CCTV	High Bit Rate Long Distance Telecoms

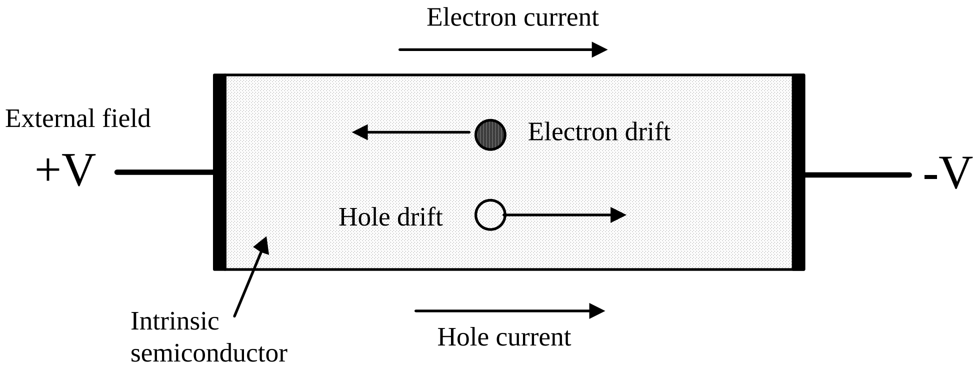
Semiconductor Basics

- In a non-conducting material, the electrons are all tightly bonded to the constituent atoms in low energy, so-called valence states.
- In conductors, a large proportion of the electrons are shared between atoms and are free to move through the atomic lattice. These occupy so-called conduction states.
- In semiconductors, most electrons are normally in valence states and there is an energy gap between the highest valence state (E_v) and the lowest conduction state (E_c), as illustrated in figure



Semiconductor Basics

- If energy is supplied, either thermally or electrically, then electrons can 'jump' the gap and be raised into the conduction band, thus increasing the conductivity of the material
- When an electron leaves a valence position in a formerly neutral atom, the 'hole' left behind therefore appears to be positively charged.
- Electricity can therefore be conducted by conduction band electrons and by holes. Electrons and holes are termed current carriers, as their motion gives rise to an electrical current, as shown in figure



Intrinsic and Extrinsic Semiconductor

- The previous basic description refers to intrinsic semiconductors, e.g. pure silicon (Si), germanium (Ge) or gallium arsenide (GaAs).

- The number of conduction electrons, n_e, is equal to the number of holes, n_h, in the valence band. Hence, we say that the number of thermally generated electron-hole pairs in the intrinsic material is

$$n_i = n_e = n_h$$

Intrinsic and Extrinsic Semiconductor

- Extrinsic semiconductors are materials which have been doped, i.e. another element has been added to replace some of its atoms.

- The new element may have a greater or lesser number of valence electrons than the intrinsic atoms and thus excess carriers are created in the doped semiconductor:

  - n - type material

    dopant, e.g. phosphorous (P), provides excess electrons

  - p - type material

    dopant, e.g. aluminium (Al), too few electrons (excess holes)

Intrinsic and Extrinsic Semiconductor

- Extrinsic semiconductors have a higher conductivity, but on their own they are not very useful.

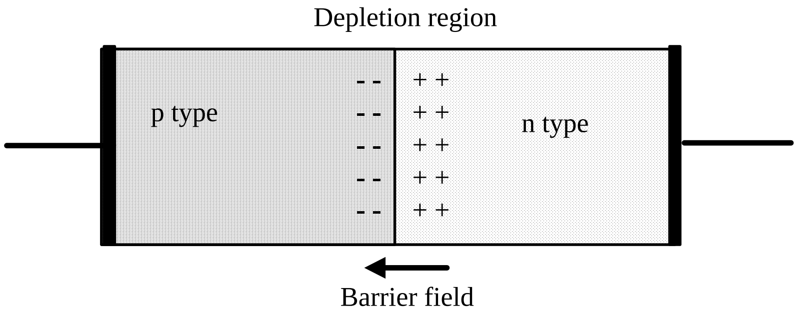
- However, when combined to form a p-n junction (commonly known as a diode) their optoelectronic potential is revealed.

P-N Junction

- When blocks of n and p type extrinsic semiconductor are brought together to form a p-n junction, the excess carriers can diffuse across the junction where they recombine and cancel each other out.

- An electric field is built up which opposes and eventually stops any further carrier motion.

- The result is a region around the junction which is depleted of carriers and across which there is an internal, built-in electric barrier field (E_B=1.6V for Si).



P-N Junction

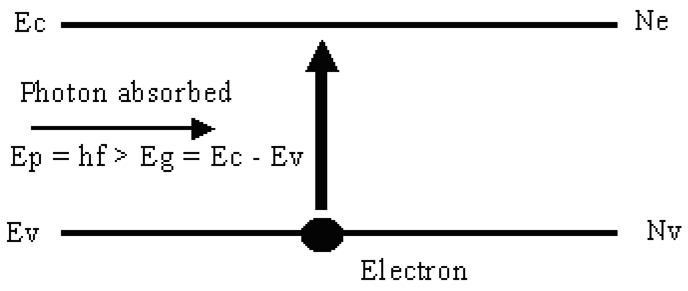
- If the p-n junction is forward biased (p positive with respect to n) then the built-in field, E_B, will be opposed by the external field, E_{ext}.
- As E_{ext} increases, current flow will initially be opposed, but the depletion region will shrink until $E_{ext} > E_B$ when current can flow unopposed.
- If the junction is reverse biased (n positive with respect to p) then the barrier field is reinforced and the depletion region grows, opposing all current flow.

Photon Absorption and Emission

- The interaction of light with semiconductors materials via three basic optoelectronic mechanisms is now considered. These mechanisms are
  - Absorption
  - Spontaneous Emission
  - Stimulated Emission

Photon Absorption and Emission

- Light consists of photons with photon energy, $E_p = hf$.
- If $E_p \geq E_g = (E_c - E_v)$, the photon can be absorbed by the semiconductor material by giving up this energy to a valence electron, thereby raising it to the conduction band and creating an electron-hole pair.
- This increases the conduction electron population, N_e, and reduces the valence electron population, N_v.

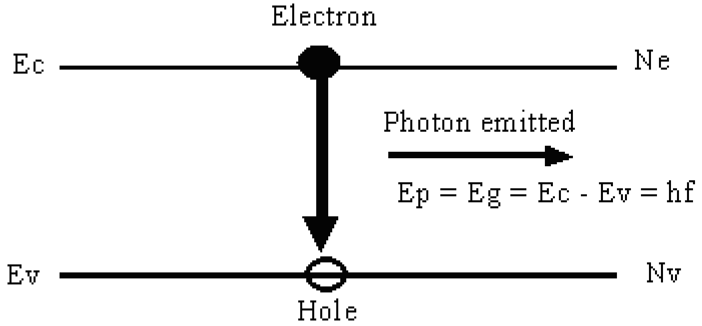


Photon Absorption and Emission

- Just as electron-hole pairs can be created by absorbing energy, they can also be destroyed by recombining with an associated loss of energy. The energy can be lost into the atomic lattice in the form of heat or it can be released as light by emitting a photon with $E_p = E_g$.

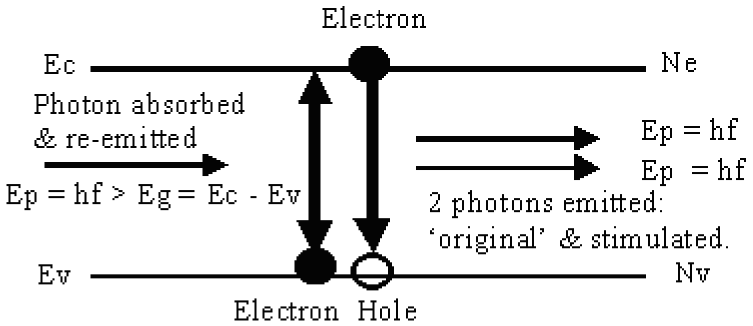
- This radiative recombination process can occur at any time and it is known as spontaneous emission of light.

- It gives rise to incoherent light as the photon emissions are independent of each other, that is they are emitted at different times from different positions within the material and in random directions.



Photon Absorption and Emission

- Large numbers of conduction electrons and holes are present, radiative recombination produces spontaneous emission of photons and these photons can then cause more photons to be emitted.
- This is a stimulated emission process, whereby the initial photon can be considered to be absorbed and then re-emitted at the same time as a radiative recombination occurs giving rise to a second photon.
- It gives rise to coherent light as the two photons have the same optical frequency, are emitted at exactly the same time, from the same position within the material and in the same direction.
- This process is repeated giving an optical gain at this frequency of light.



Absorption and Emission Rates

- A series of coupled equations can be written which describe the rates at which the three optoelectronic processes occur within a particular material. These are called Einstein relations.

  – Rate of spontaneous emission: $R_{spon}=AN_2$

  – Rate of stimulated emission: $R_{stim}=BN_2\rho(f)$

  – Rate of absorption emission: $R_{abs}=B'N_1\rho(f)$

  where

  - N_1,N_2 are the atomic densities of ground (valence) and excited (conduction) states
  - $\rho(f)$ is the spectral density of photon energy
  - A,B,B' are constants (the Einstein coefficients)

Absorption and Emission Rates

- At thermal equilibrium : $(N_2/N_1) = \exp(-E_g/k_BT)$

  where

  k_B is the Boltzmann's constant

  T is the absolute temperature

- In terms of rate, equilibrium means that

$$AN_2+BN_2\rho(f)=B'N_1\rho(f)$$

  and therefore,

$$\rho(f)=(A/B) / \{ (B/B')\exp(hf/k_BT)-1\}$$

- Now, in general, light has a Plank distribution given by

$$\rho(f)=(8\pi hf^3/c^3) / \{ \exp(hf/k_BT) -1 \}$$

  obtaining

$$A=(8\pi hf^3/c^3)B \quad \text{and} \quad B'=B$$

Absorption and Emission Rates

- Several conclusions can now be drawn
  - If $k_B T \approx hf$ then $R_{spon} > R_{abs}$ & R_{stim}

    i.e. mostly spontaneous emission: this is true for thermal light source e.g. light bulbs or candles.

  - For $hf \approx 1$ eV (visible/near infrared region) $R_{spon} >> R_{stim}$

    i.e. at room temperature ($T \approx 300$K) thermal light sources are incoherent.

  - For $R_{stim} >> R_{spon}$

    i.e. coherent light source: Derivation shows this cannot occur unless external energy is supplied to force the system away from equilibrium.

  - For $R_{stim} >> R_{abs}$

    i.e. stimulated emision dominates and optical gain is possible: Requires that N2 > N1, this is called a **population inversion**.

Injection Luminescence

- At equilibrium the depletion region and the 'built -in' electric field stops carrier diffusion and current flow. The depletion region has no free carriers and therefore no recombination can occur

- Under forward bias, the external field reduces the built-in field and carriers diffuse across the junction, giving rise to an electric current.

- The external circuit "injects" carriers into the depletion region where electrons & holes are thus present simultaneously. These may recombine by spontaneous or stimulated emission creating an optical source.

- The process by which radiative recombination emit light from a forward biased p-n junction diode is called **injection luminescence**.

Injection Luminescence

- We define an internal quantum efficiency

$$\eta_{int}\ (\%) = (R_{rr} / R_{total})\ \times 100$$

where
  - R_{rr}, R_{nr} are rates of radiative & non-radiative recombination, respectively
  - $R_{total} = R_{rr} + R_{nr}$ is the carrier injection rate
  - $R_{rr} = R_{spon} + R_{stim}$

- For LEDs: $R_{spon} >> R_{stim}$; $R_{spon} \approx R_{nr}$ -> $\eta_{int} \approx 50\%$

- For SLDs: $R_{stim} >> R_{spon}$ -> $\eta_{int} \approx 100\%$

Light Emitting Diode (LEDs)

- The simplest LED structure is a forward biased p-n junction.
- Light is generated in the depletion region by injection luminescence. Some photons escape from the material and may be coupled into an optical fibre.
- This structure is called a homojunction, as the p and n type materials are formed from the same semiconductor with different dopants.
- Recombination occurs over a region $\approx$ 10 µm wide as the carriers are not well confined, giving a low carrier density and reducing the likelihood of recombinations.

Light Emitting Diode (LEDs)

- If a thin layer of lower bandgap material is sandwiched between the p & n regions the injected carriers are effectively confined to form a narrow active region ($\approx$ 0.1 μm).

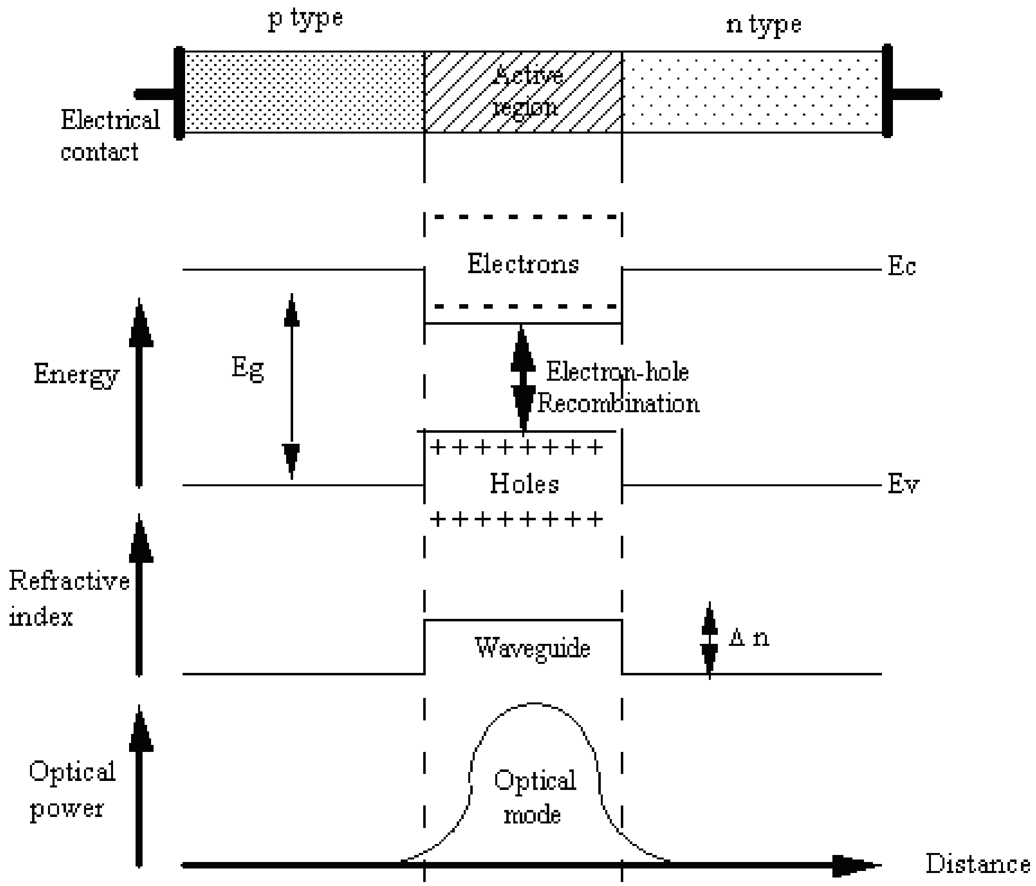
- The higher carrier density means that the quantum efficiency increases and the same optical power can be produced with a lower externally supplied injection current.

- To produce a lower bandgap requires a different semiconductor, hence this structure is called a heterojunction.

- A consequence of the lower bandgap is a slightly higher refractive index, hence this structure also forms an optical waveguide which helps to confine the light produced such that it is emitted from a smaller area of material.

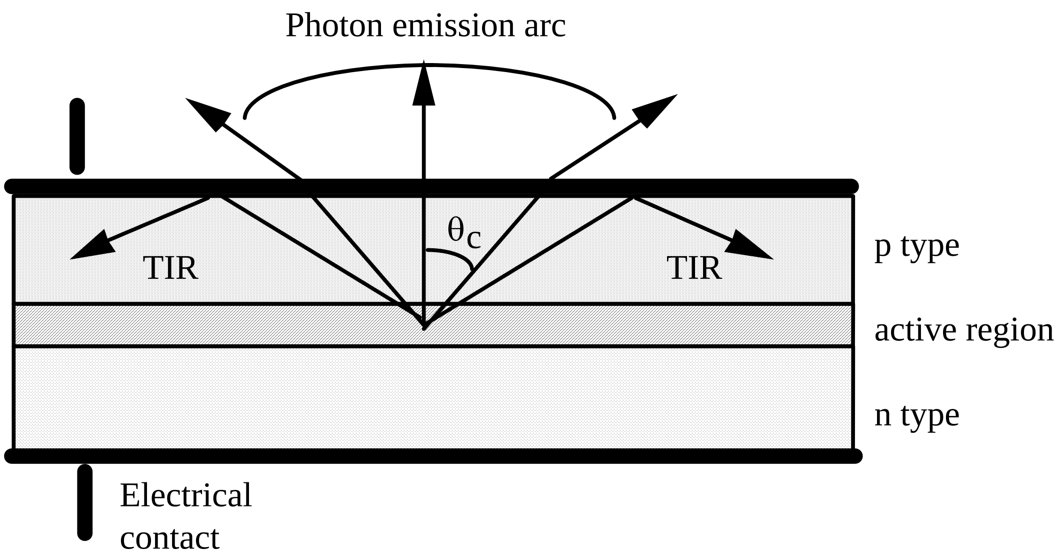
Light Emitting Diode (LEDs)

- The figure below illustrates the formation of a waveguide within the heterojunction structure.



Light Emitting Diode (LEDs)

- The light emitted is incoherent (spontaneous emission only), the spectral width is typically, $\Delta\lambda \approx 30 \rightarrow 60$ nm, and the angular spread $\approx 100°$ (>> fibre NA) as shown in figure.



Light Emitting Diode (LEDs)

- An injection current, I, gives a carrier injection rate = (I/q) s^{-1}.

- Rate of photon generation is

$$(\eta_{int}\ I/q)\ s^{-1}$$

  therefore the internal optical power generated

$$P_{int} = [\eta_{int}\ (I/q)\ hf\ ]\ \ \text{Watts}$$

- Power losses include:
  - Photon re-absorption
  - Total internal reflection at air-semiconductor interface (refractive index of semiconductor ≈3.5)

- The external optical power is

$$P_{ext} = \eta_{ext} P_{int}$$

  with
  - η_{ext} external quantum efficiency.

Light Emitting Diode (LEDs)

Example:

For $\eta_{int} = 0.5$, $I = 50mA$, $f = 2 \times 10^{14}$ Hz

$\rightarrow$ $P_{int} \approx 20mW$ $\rightarrow$ $P_{ext} \approx 280\ \mu W$

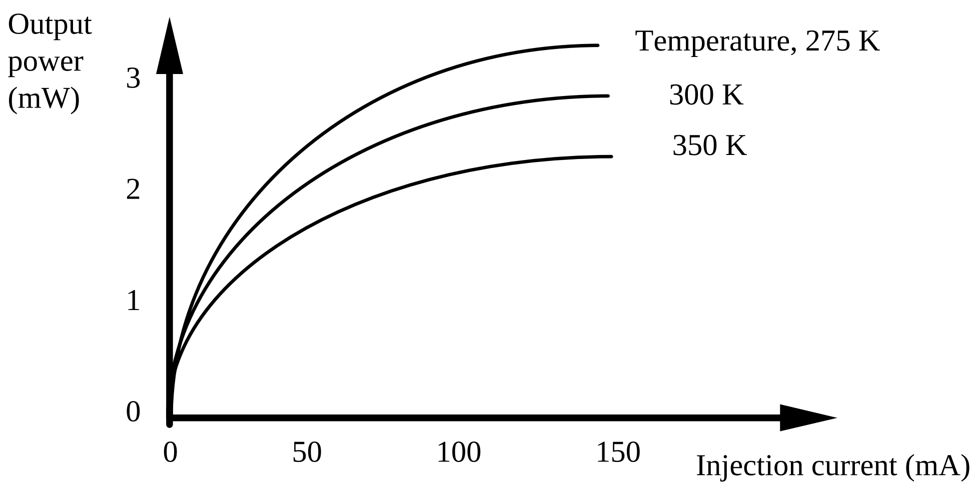
Most of P_{ext} within angular spread ≈ 100°: however, fibre acceptance angle (x2) ≈ 30° max, therefore power launched into fibre < 100μW.

Light Emitting Diode (LEDs)

- The overall optoelectronic conversion efficiency is called the responsivity, R, of the device.

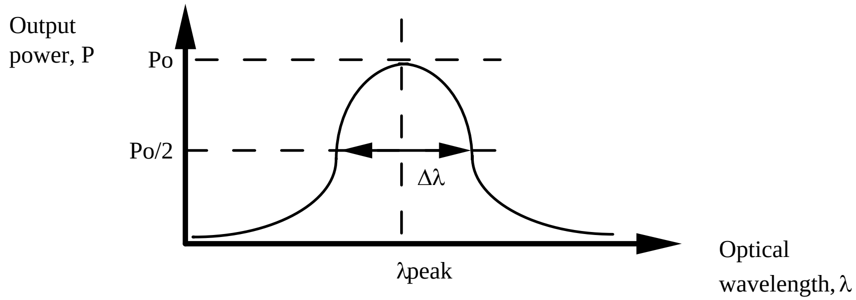
$$R \ (WA^{-1}) = (P_{ext} / I) \quad (= \eta_{ext} \, \eta_{int} \, (hf / q))$$

- $R_{nr} \propto T$ therefore $\eta_{int} \propto 1/T$.



Light Emitting Diode (LEDs)

•A typical spectral distribution of the output light is given in figure below. The spectral width, $\Delta\lambda$, is defined as the full width wavelength spread at half maximum power.



•The peak wavelength occurs at, $\lambda_{peak} \propto T$, and: $\Delta\lambda$ (FWHM) $\propto T\,\lambda^2_{peak}$

•Typically,

- $\Delta\lambda \approx 30$ nm @ $\lambda = 0.85$ µm
- $\Delta\lambda \approx 60$ nm @ $\lambda = 1.3$ µm
- $\Delta\lambda \approx 90$ nm @ $\lambda = 1.55$ µm

Light Emitting Diode (LEDs)

•The modulation frequency response is limited by carrier lifetime, τ_c, which is the time that carriers take to cross the depletion region and thus the time during which electrons and holes co-exist and can recombine. If the carrier density varies with time as N(t)

$$R_{spon} + R_{nr} = N(t) / \tau_c$$

•Thus if we have a sinusoidal modulation current, I_{MOD}, in addition to a D.C. bias current, I_{BIAS}:

$$I(t) = I_{BIAS} + I_{MOD} \exp (j\omega_m t)$$

then

$$N(t) = N_{BIAS} + N_{MOD} \exp (j\omega_m t)$$

Light Emitting Diode (LEDs)

•Assuming a linear response the power transfer function is given by

$$(N_m(\omega_m) / N_m(\omega_m=0)) = (1 / (1 + j\omega_m\tau_c))$$

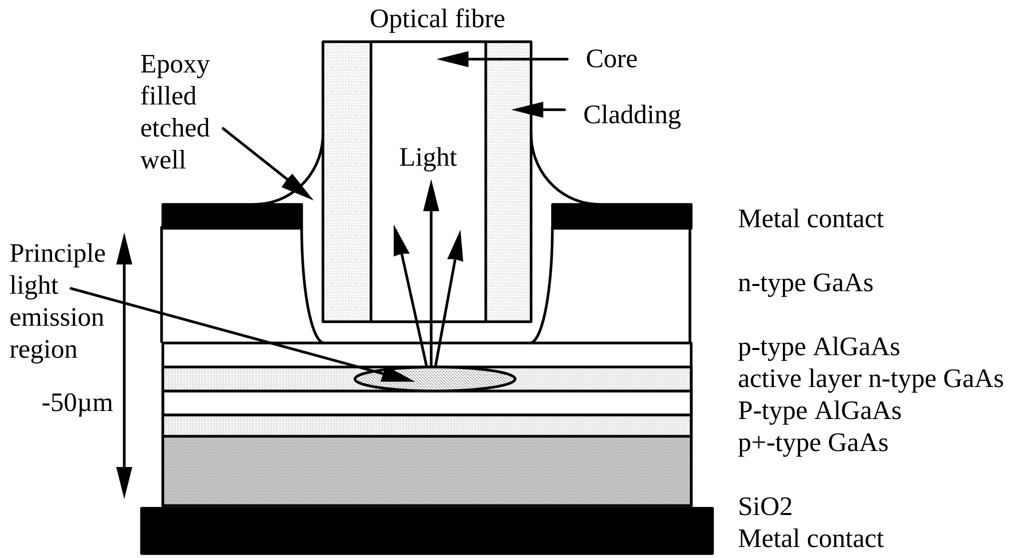
therefore power falls to 1/2 its maximum value when real part equals imaginary part, i.e. 1= wm tc, hence at a frequency given by

$$f_{3dB} = 1 / (2\pi\tau_c)$$

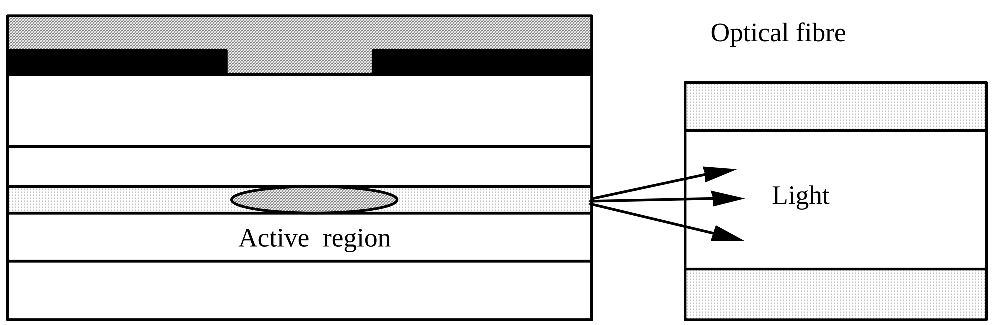
•Typically, tc ≈ 2 - 5 ns giving an LED modulation bandwidth ≈ 30 – 80 MHz.

Light Emitting Diode (LEDs)

- Figures below show two type of LED transmitter designs, whereby the emitted light is coupled into an optical fibre via the top surface or the edge of the diode.



surface emitter



edge emitter

Semiconductor Laser diodes (SLD)

- The light is produced by stimulated emission and is thus coherent and emitted over a smaller angular spread.

- It can be more tightly confined and permits a much higher efficiency of coupling into an optical fibre.

- Increased quantum efficiency means higher output optical power, typically 3-10mW.

- SLDs also have narrower spectral widths and higher modulation bandwidths.

Semiconductor Laser diodes (SLD)

- Laser operation requires two conditions to be fulfilled

  – Optical gain

  provided by stimulated emission mechanism which requires a population inversion - provided by forward biasing a very highly doped p-n junction.

  For an indium gallium arsenide (InGaAs) heterostructure SLD with an operating wavelength =1.3µm, the gain coefficient

  $$g \propto R_{stim} - R_{abs} < 1$$

  for carrier densities

  $$N < 10^{18}\ cm^{-3}$$

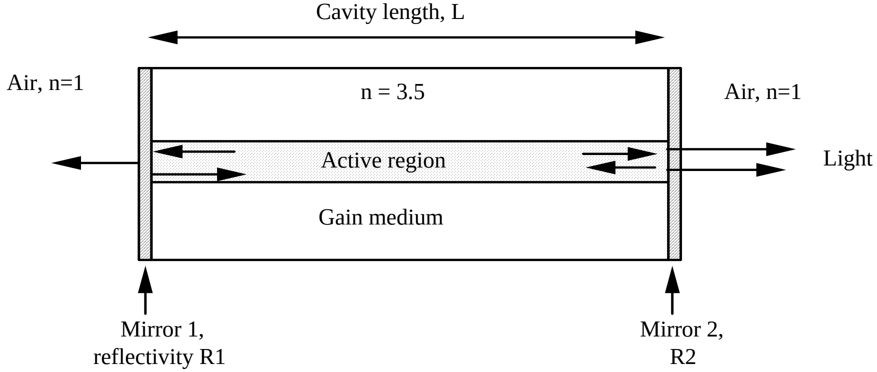
  Population inversion occurs for $N \approx 1.3 \times 10^{18}\ cm^{-3}$ then g increases linearly with N.

  $N \approx 2 \times 10^{18}\ cm^{-3}$ gives $g \approx 300$.

Semiconductor Laser diodes (SLD)

– Optical feedback

The rate of stimulated emission must be sufficiently high to overcome losses and sustain laser action. This requires the formation of an optical cavity about the gain medium to reflect light back into the gain region to provide positive feedback. A heterostructure confines the light within an active region waveguide and mirrors are formed on each end of the laser's active region simply by cleaving the faces to be parallel. The difference in refractive index between the semiconductor and the air gives a mirror with a reflectivity of ≈30%. Consequently, 70% of the light escapes to be coupled to a fibre, but 30% is reflected back into the cavity to be re-amplified as it passes through the active area. This design, called a Fabry-Perot cavity, is shown schematically in figure.



Semiconductor Laser diodes (SLD)

•As the light is coherent, it will interfere with itself, that is to say that two beams will either reinforce or cancel out each other depending on whether they are in or out of phase.

• As the relative phase depends on the wavelength of the light, this means that optical power at a specific wavelength (and integer multiples) for which this phase matching is perfect, will build up quicker than all other wavelengths.

•This wavelength selection narrows the spectral width of the output light. The phase matching condition is met for all optical frequencies defined by:

$$f_m = (m\ c\ /\ 2\ n\ L)$$

where

- m is an integer.
- n is the refractive index of the cavity.
- L is the cavity length.

Semiconductor Laser diodes (SLD)

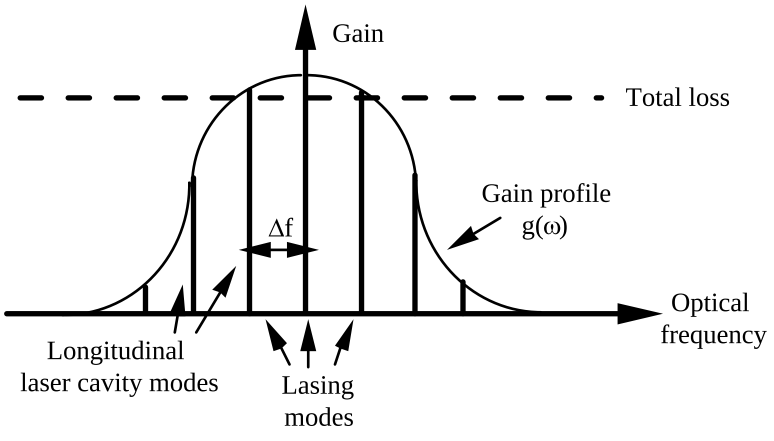
•These are known as the longitudinal mode frequencies and are spaced by

$$\Delta f = (c / 2nL)$$

– Example:

For L = 200 - 400 µm, n=3.5, Df = 100 - 200 GHz

•Figure below is a schematic of the gain profile as a function of optical frequency. It shows that several longitudinal modes may experience sufficient gain to overcome the loss threshold and the laser will lase on several different modes at once, thereby significantly broadening the effective spectral width.



Semiconductor Laser diodes (SLD)

- At injection currents below threshold, the laser emits incoherent spontaneous emissions and thus behaves as an LED.

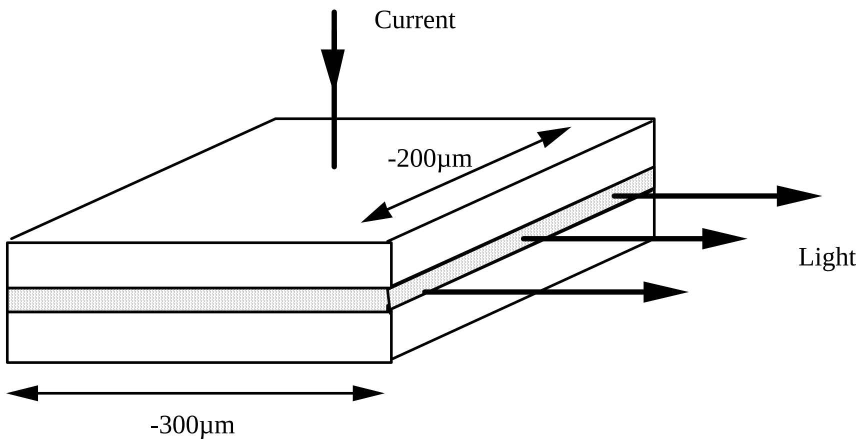
- At injection currents around threshold, the laser starts to emit on many longitudinal modes.

- As the injection current rises a few laser modes become dominant and all the optical power is concentrated within these modes.

- The spectral width of these multimode lasers (2-5nm) limits BL to $\approx$10Gbs^{-1}-km

Semiconductor Laser diodes (SLD)

•Just as longitudinal modes are due to phase matching over the length of the cavity, L, so transverse modes are related to the width, W of the cavity. Simple p-n heterostructures emit over the full width (say 200µm) of the device as shown.



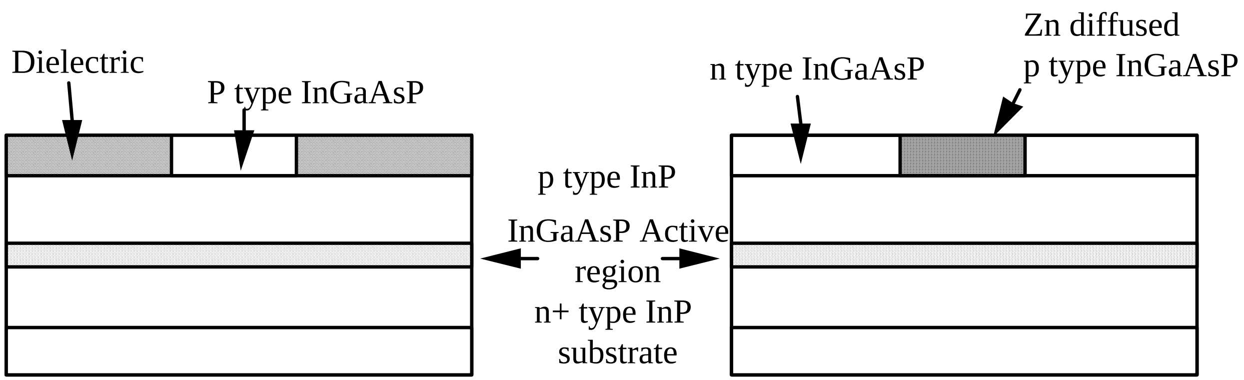
•The length, L must be sufficient to give adequate gain and thus cannot be reduced to reduce the number of longitudinal modes.

•However, to increase efficiency, it is desirable to restrict the number of transverse modes and thus the width of the emission area. This can be achieved by two design improvements:

Semiconductor Laser diodes (SLD)

- Gain guided structures

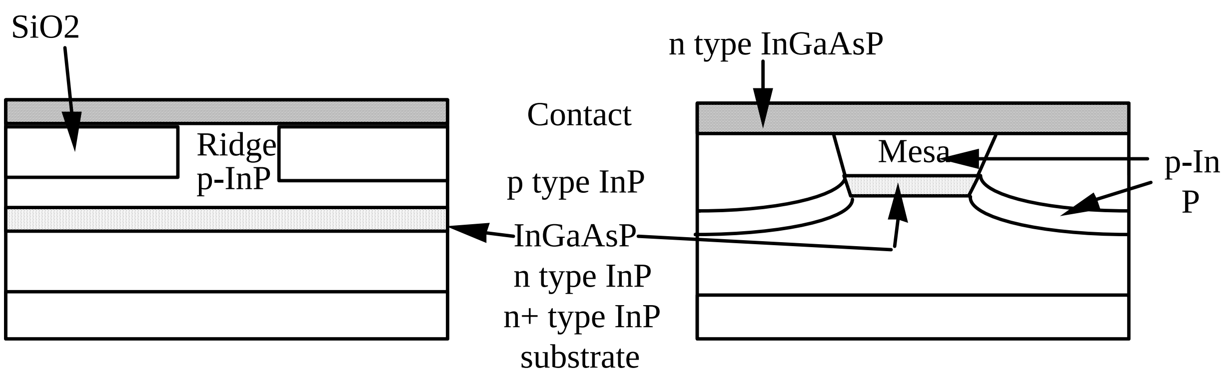
Using a stripe geometry within the p region, current injection occurs over a narrower section of the depletion region and changes its refractive index forming a waveguide. The width of the active region depends on the current density, as does the optical gain. Hence, the emitted spot size (typically 1 x 10µm) depends on the output optical power which is undesirable. Two stripe geometries are shown in figure.



Semiconductor Laser diodes (SLD)

• Index guided structures

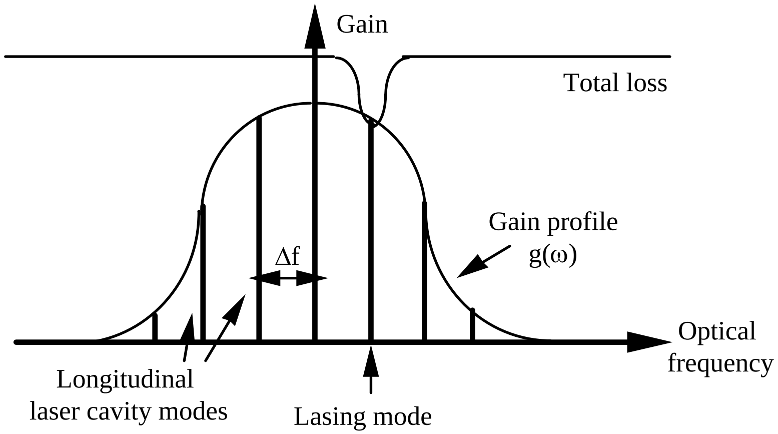
Figure shows schematics of two index guided structures where lateral waveguiding is provided by forming the active region within a ridge or mesa, bounded by lower refractive index materials. Active region dimensions ≈ 0.1 x 1µm. These buried heterostructures provide improved transverse confinement but are more expensive to produce.



Semiconductor Laser diodes (SLD)

•The laser performance can be further enhanced by structures which permit only single longitudinal mode (SLM) operation.

•This requires the introduction of frequency dependent loss so that the loss profile is no longer flat and one longitudinal lasing mode crosses the gain threshold well before any other and may thus dominate. This is shown schematically in figure.



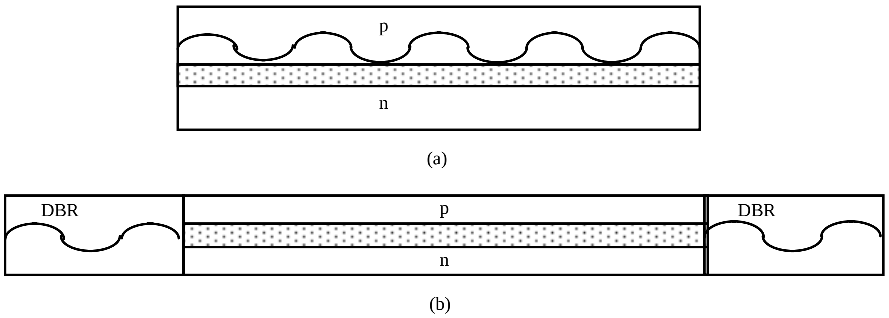
•The neighbouring modes will never cross the threshold and thus the power in these modes will be <1% of the total. We define a mode suppression ratio,

MSR = (Power in main mode / Power in side modes)

Semiconductor Laser diodes (SLD)

•For a good single longitudinal mode laser, MSR > 1000 (30dB). Structures which can be used for SLM operation are shown.

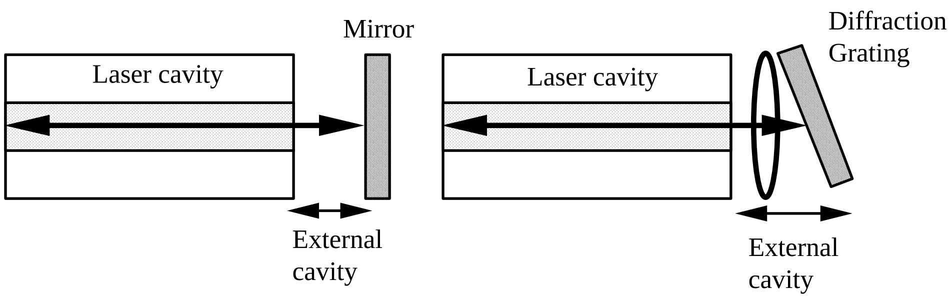
•The figure shows designs based on distributed feedback, whereby a diffraction grating is built into the p region or the cavity mirrors are gratings. The grating reflectivity is frequency dependent providing the required loss mechanism.



(a) Distributed feedback (DFB) laser with integral diffraction grating
(b) Distributed Bragg reflection (DBR) laser

Semiconductor Laser diodes (SLD)

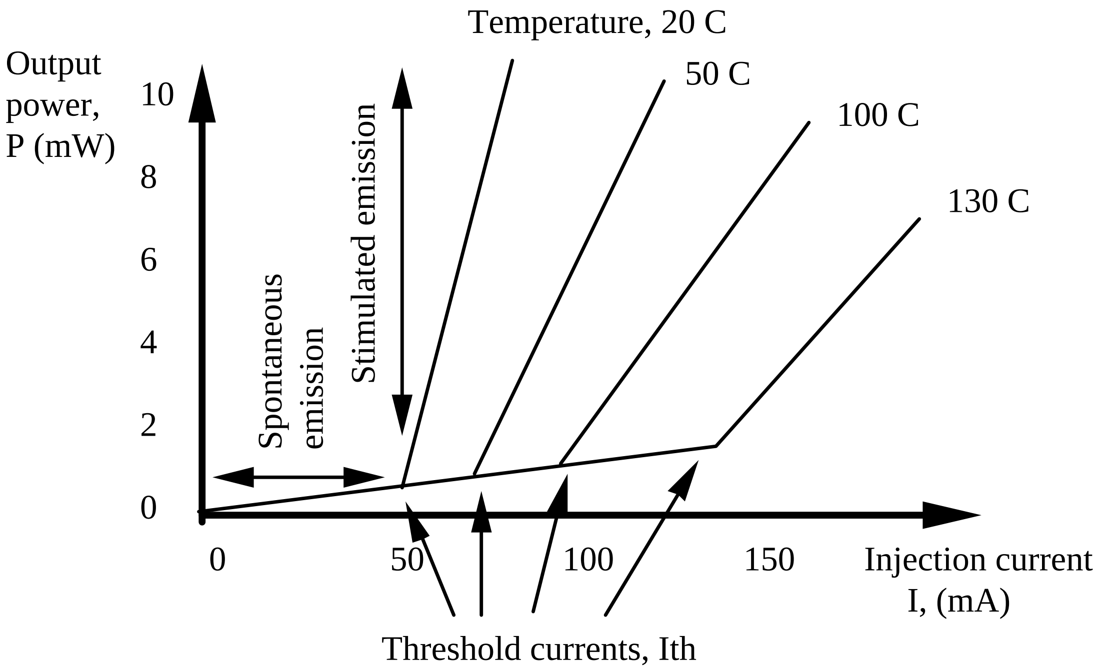
•Figure shows two coupled cavity designs, one with a second Fabry-Perot cavity and one with an external diffraction grating (reflected wavelength depends on tilt angle). These only lase on the longitudinal mode which satisfies the phase matching condition for both cavities. By allowing the length of the Fabry-Perot or the tilt angle of the grating to be mechanically adjusted, the optical frequency of these lasers can be tuned



(a) External Fabry-Perot cavity
(b) External diffraction grating

Semiconductor Laser diodes (SLD)

•The output characteristic of a typical laser is shown in figure for several temperatures. The temperature dependence is primarily due to increasing non-radiative recombinations which increase the threshold current and decrease the efficiency and thus the slope of the characteristic as shown.



•When the internal efficiency and mirror losses are combined, the overall optoelectronic conversion efficiency is ≈ 50 - 80%.

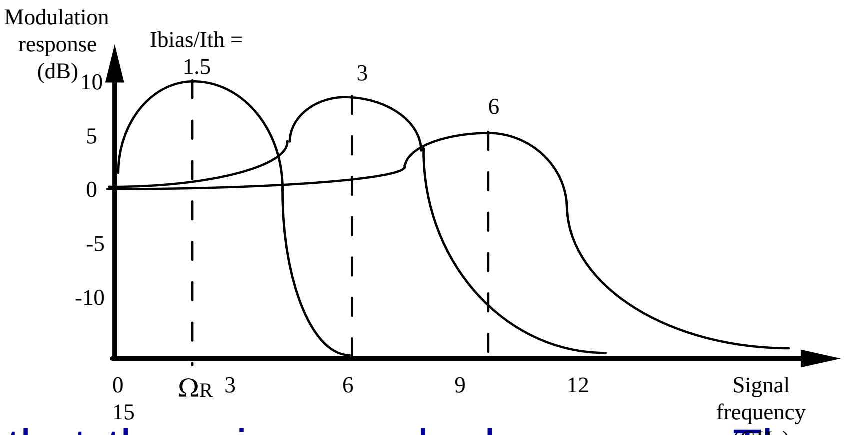
Semiconductor Laser diodes (SLD)

•Another effect of a temperature change is that the output wavelength changes. Larger changes can occur if the laser output wavelength 'mode-hops', that is it jumps from one dominant mode to another giving a change of ≈0.5nm. Mode hopping is an unpredictable event and multiple random hops gives rise to extra noise on the output.

•Intensity modulation is achieved by varying the bias injection current. This alters the carrier concentration and thus the gain, thereby varying the output power. However, this also changes the temperature within the cavity and thus modulates the wavelength as described above. Hence, intensity modulation is always accompanied by frequency modulation (frequency chirping). Injection current induced frequency modulation is ≈ 2GHz.mA^{-1}.

Semiconductor Laser diodes (SLD)

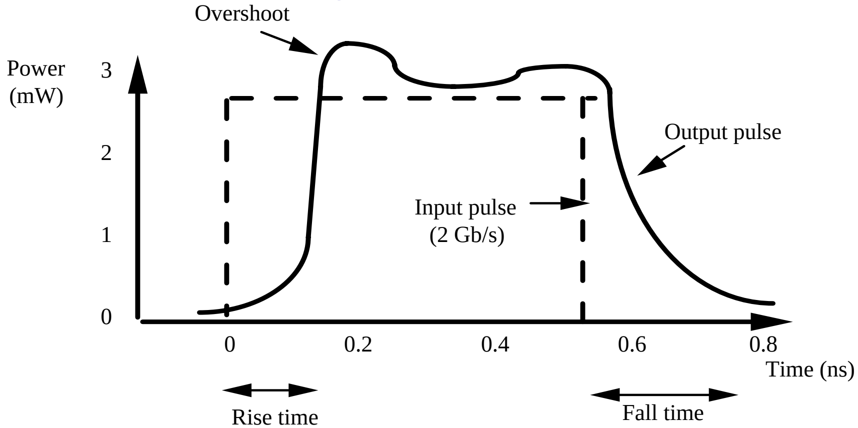
•At low frequencies the thermal change induces greater modulation than the carrier density change, but this is reversed at higher frequencies. Thus at high frequencies, df/dI ≈ 0.2GHz.mA^{-1}. The modulation bandwidth is a complex function depending on carrier density, carrier lifetime, cavity index and gain, and photon lifetime within the cavity. The typical small signal response is shown schematically in figure as a function of modulation frequency.



•It can be seen that there is a peaked response The peak occurs at what is known as the relaxation oscillation frequency, WR, which is proportional to the ratio of the bias and threshold currents. Modulation bandwidths can theoretically be as high as 40GHz.

Semiconductor Laser diodes (SLD)

•Possibly of more importance for intensity modulation schemes is the large signal response, as illustrated in figure.



•To achieve digital optical communication using intensity modulation, the laser is biased close to threshold to give almost zero output for a '0' bit and well above threshold for a '1' bit. The speed at which the laser can react to a change from 0 to 1 and vice-versa is governed by the rise and fall-times (usually taken between 10% and 90% of maximum output). Figure shows bandwidth limiting pulse distortion due to the rise-time and fall-time and overshoot due to 'ringing' at the relaxation oscillation frequency. The rise and fall times thus correspond to the delays before lasing occurs and ceases. Combined with parasitic capacitance this means that the maximum direct modulation bit rate is usually limited to <10GHz.

Semiconductor Laser diodes (SLD)

- Noise on the laser injection current will also directly intensity modulate the output. This can be reduced using current feedback drive circuitry to operate the laser at constant (mean bias) current or constant (mean) output power.

- There are several additional noise mechanisms fundamental to laser operation:

- Spontaneous emissions

These are the dominant noise source. These are random and although much smaller than the stimulated emission, contribute a noise power to the optical output.

- Electron-hole recombinations

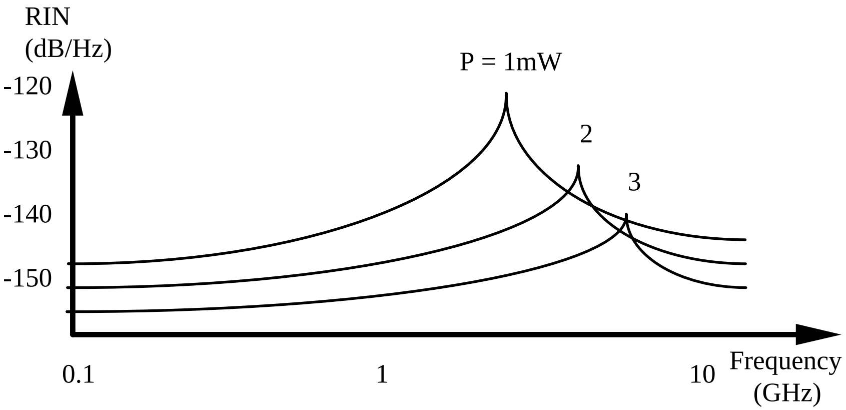
These contribute a form of shot noise due to the random injection of carriers and the random time of recombination. As well as limiting signal to noise ratios with intensity noise, they also give rise to phase fluctuations which effectively increase the spectral width.

Semiconductor Laser diodes (SLD)

•Thermal noise

This is generated in all resistive components.

•The frequency distribution of the intensity noise in the output of the laser is shown in figure. The relative intensity noise (RIN) is equivalent to the frequency distribution of the noise output. This gives a spectral response in dB/Hz and can be seen to be a peaked response. The peak moves to higher frequencies for increasing mean output power.



(1.55μm InGaAsP SLM laser)

Semiconductor Laser diodes (SLD)

- The RIN may be increased by mode partition noise due to random redistribution of optical power between main and side laser modes. This is dependent on the mode suppression ratio.

- However, the signal to noise ratio of the output always improves as the mean power increases.

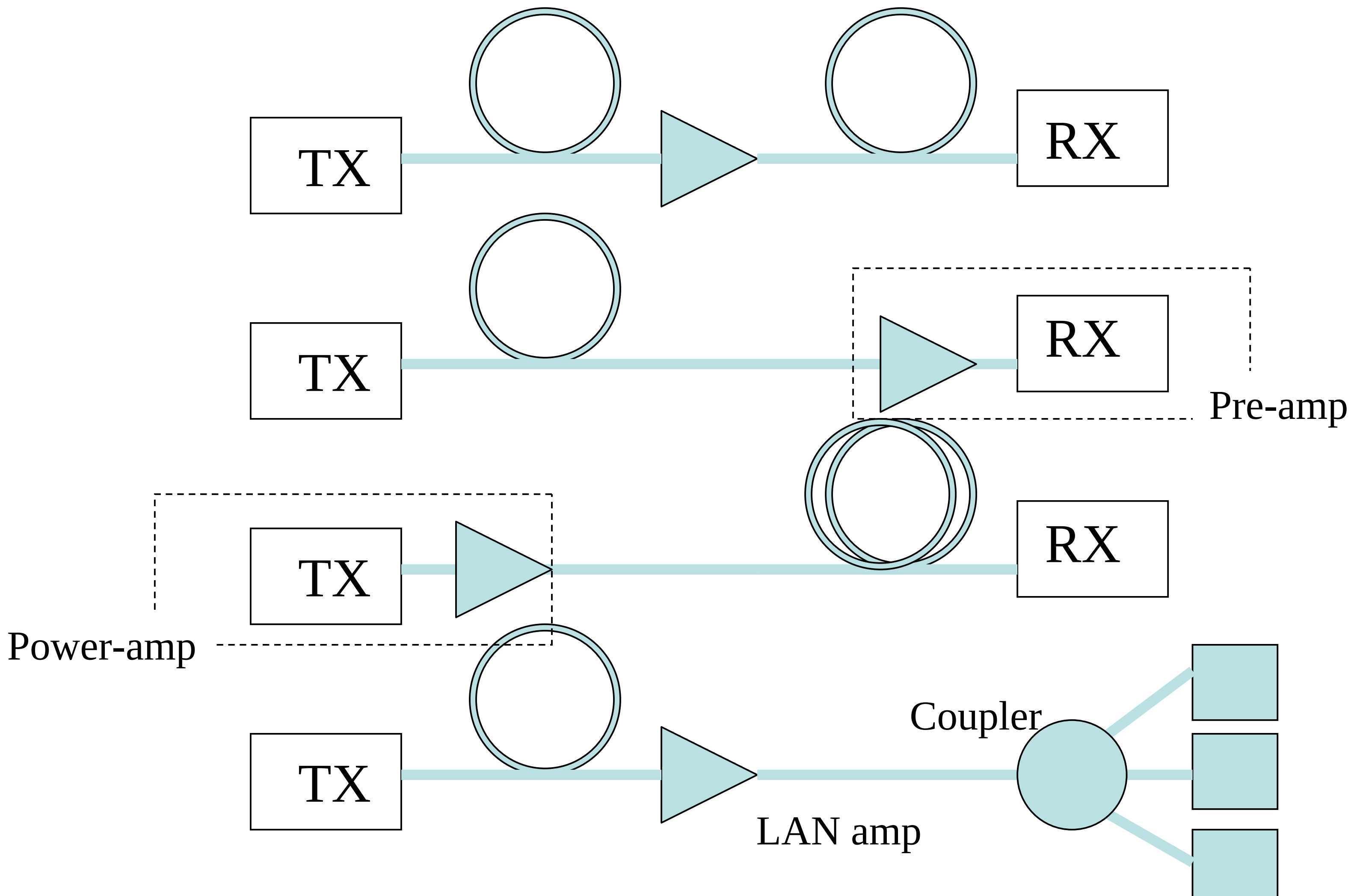
- The spectral linewidth also decreases as the mean power increases up to ≈10mW. After this it can only be reduced further using complex laser structures such as the SLM devices described above and multiple quantum well devices.

- Multimode laser Δf > 200GHz @ 1.55μm
- MQW-DFB SLM laser Δf > 0.3MHz @ 1.55μm

Optical Amplifiers

- Formulate a power budget
- Add repeaters at appropriate intervals
  - Photon to electron to photon amplifiers
  - All photon amplifiers
- Current technology is all photon based
  - Semiconductor optical amplifiers
  - Doped-fibre amplifiers

Applications



Fibre amplifiers

- “Rule of thumb”
  - Each fibre channel should have an SNR of order 100 and about 0.1 mW optical power at receiver
- Erbium doped fibre amplifiers (EDFA)

  An Er doped glass fibre segment pumped at 980 nm or 1480 nm provides gain in region 1510 to 1600 nm (peaking around 1550 nm)

  Flat gain region between 1530 and 1565 nm allows dense wavelength division multiplexing (DWDM)

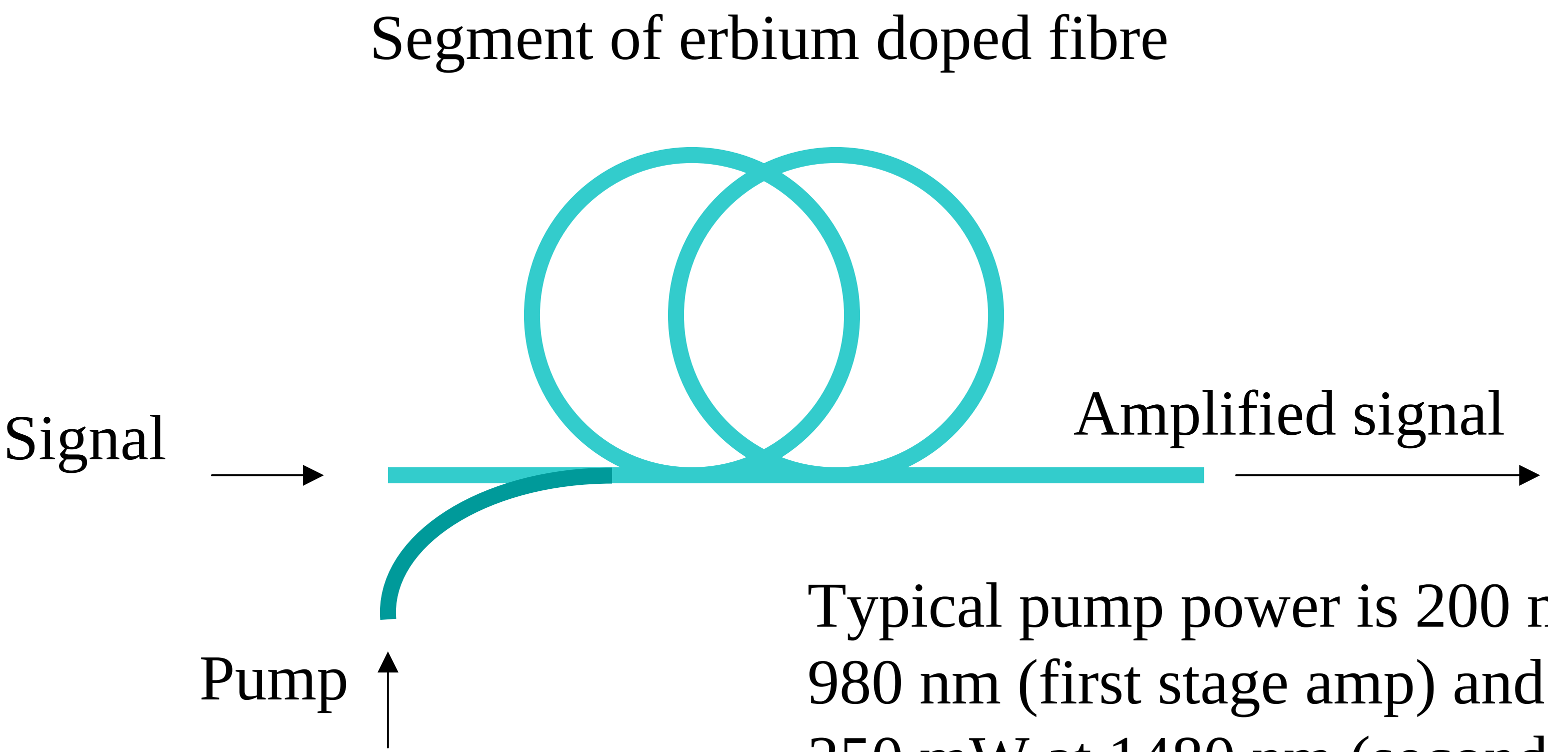
Wavelength Division Multiplexing

- Same principle as Frequency-division multiplexing in microwave and satellite radio systems
- Capacity upgrade of exiting fibres
- Each channel can carry any transmission format
- Routing using wavelength in *addition* to time and space routing.

Wavelength Division Multiplexing

- Modulated output of DFB lasers has very narrow spectrum. Can operate several with 100 GHz mean spacing (now moving to 50 GHz spacing)
- Low loss windows at 1310 nm and 1550 nm are about 15 THz wide.
- Thus of order one hundred 20 Gb/s channels per fibre = 2 Tbit per second per fibre!
- Ideally all carriers are *orthogonal* (but need to worry about non-linear effects such as Brillouin scattering and 4-wave mixing in practice)
- Need very broad band optical amplifiers

Fibre amplifiers: EDFA Principle



Typical pump power is 200 mW at 980 nm (first stage amp) and 250 mW at 1480 nm (second stage).

EDFA in practice

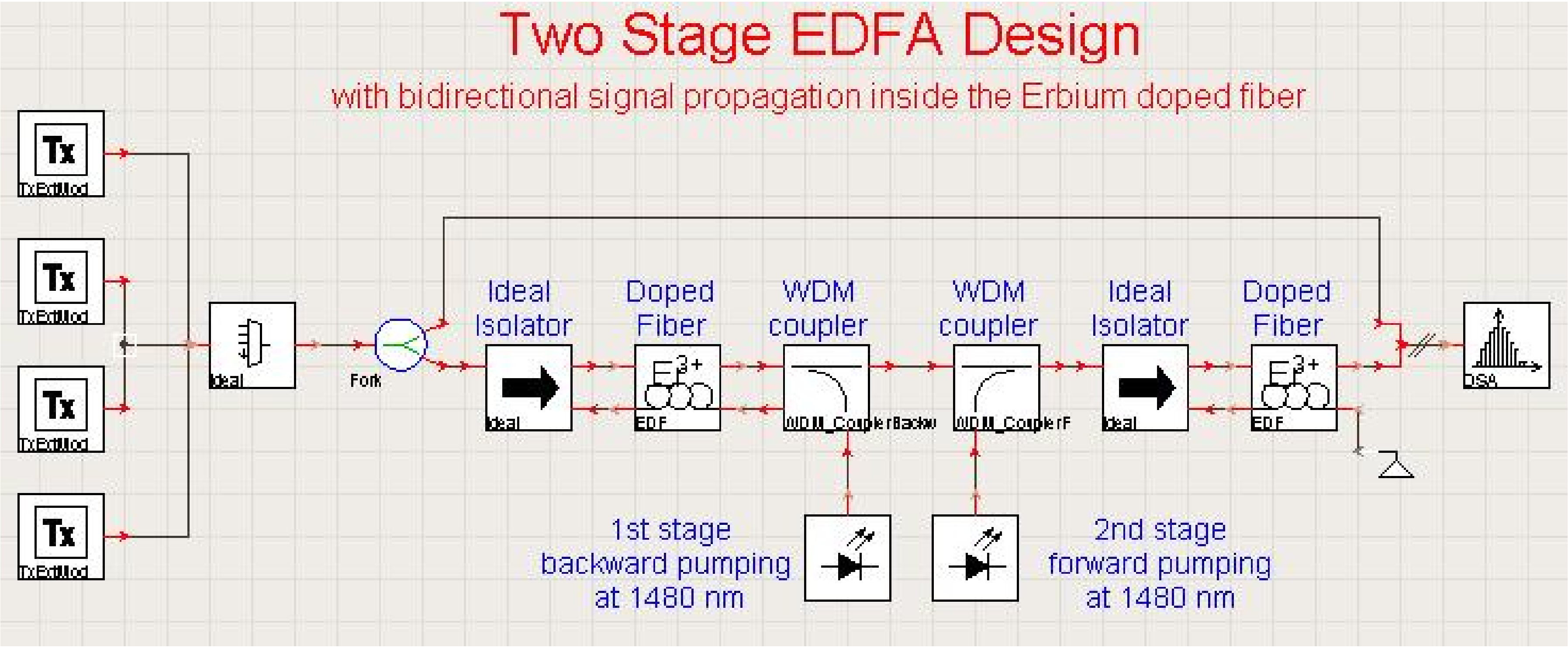
- Power amp after low power emitter
- Line amp every 80 km
- Pre-amp just before receiver

Amplifiers typically support up to 80 DWDM channels. *Uniformity of gain across the channels is critical*.

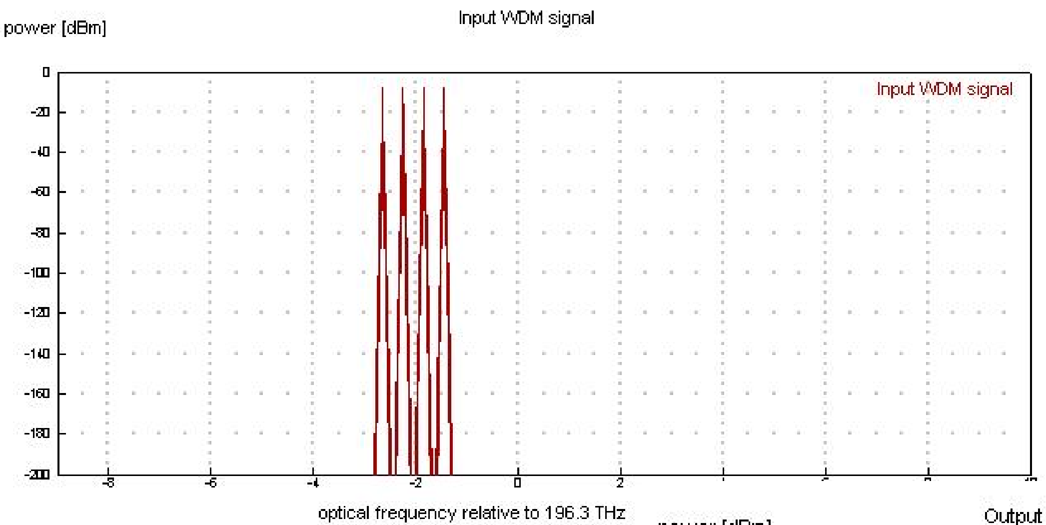
Recently DWDM has expanded into the region 1570 to 1620 nm (L-band) but it has lower gain in this region.

Current development of the Raman Amplifier is promising

EDFA amplifier simulation

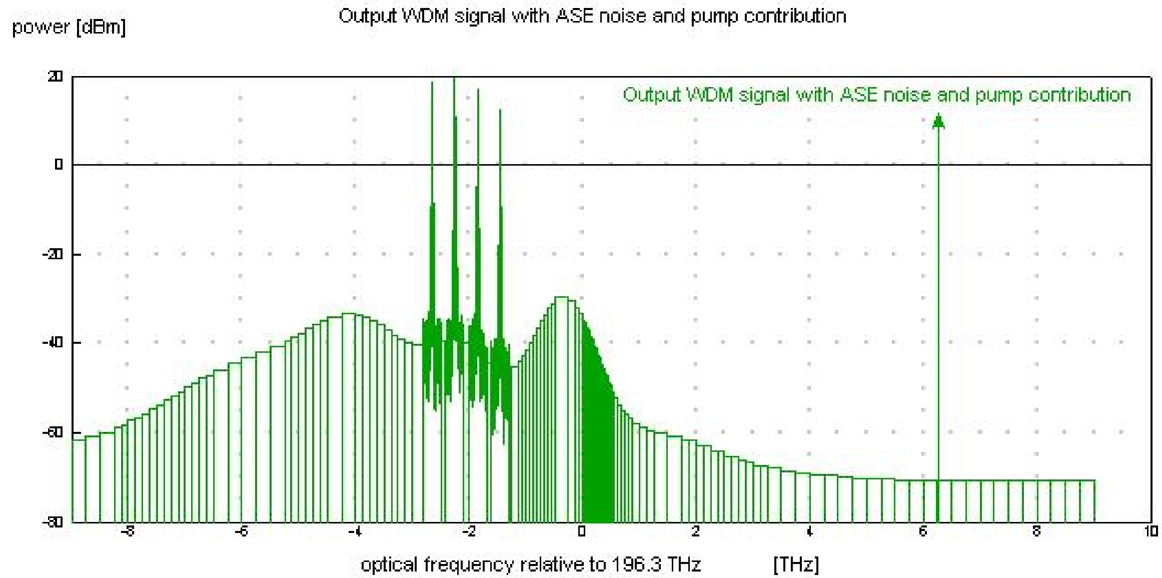


Simulation



Four input signals spaced by 400 GHz.

Output from two stage EDFA repeater showing signal plus noise.



Real EDFA Amplifier

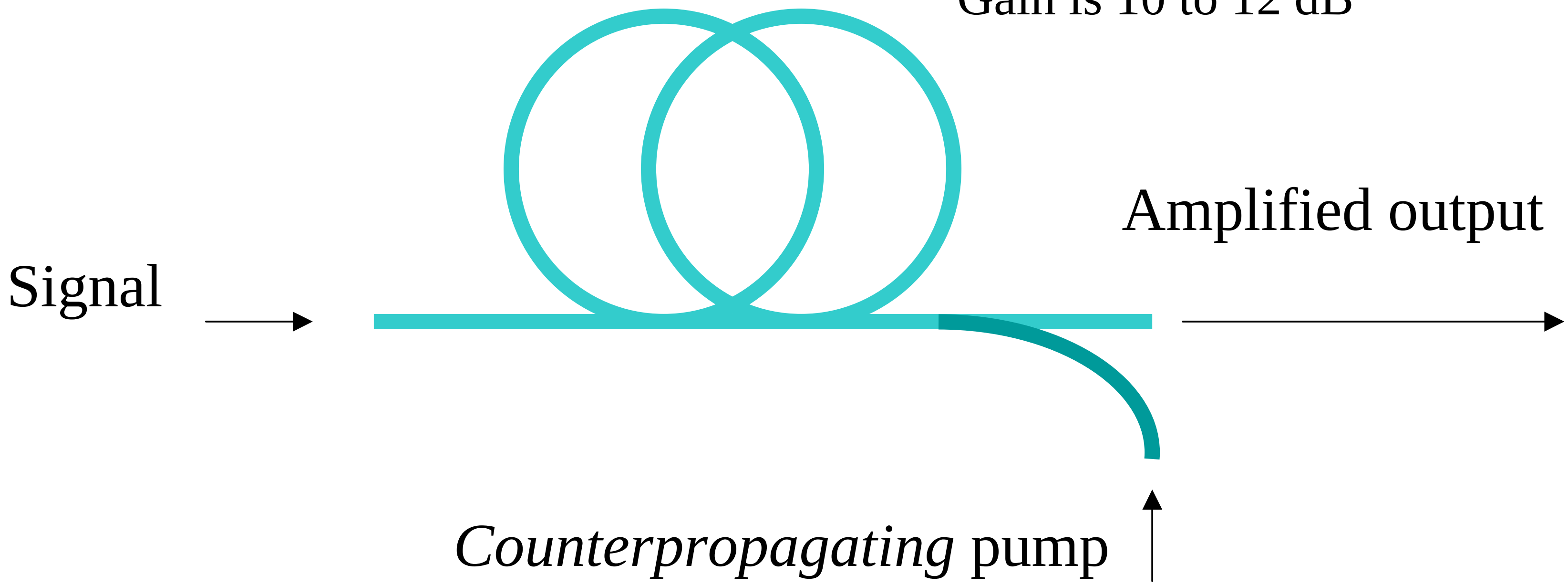
JDS Uniphase OA4000R series (see http://www.jdsu.com/)

Specifications

Parameter	OAR-21F4200Cx	OAR-22F4300Cx
Signal wavelength	1530.33 to 1561.42 nm	
Total input signal power	3.5 to 6.5 dBm	9 to 12 dBm
Total output signal power	21 dBm	22 dBm
Signal gain (design point)	14.5 to 17.5 dB	10 to 13 dB
Flatness	1.0 dB	
Noise figure per channel	9.6 dB	11.9 dB
Gain transient suppression time	see table below	
Gain transient overshoot/undershoot	see table below	
Mid-stage access loss	12 dB	10 dB
Power supply requirement	5 and ±12 V	
Dimensions (W x H x D)	200 x 130 x 31 mm	
Operating temperature	0 to 65 °C	

Fibre amplifiers: Raman

Typically two lasers with
250 mW power at 1427 nm and
1467 nm are used to pump.
Gain is 10 to 12 dB



Real Raman Amplifier (JDS Uniphase)

Specifications

Parameter		X-RPU-C (C-band)	X-RPU-L (L-band)
Wavelength range		1528 to 1562 nm	1570 to 1612 nm
Pump power output	Minimum	550 mW	550 mW
Pump degree of polarization	Typical	5.0%	5.0%
	Maximum	7.5%	7.5%
Insertion loss over C-band	Typical	0.8 dB	-
	Maximum	1.1 dB	-
Insertion loss over L-band	Typical	-	0.8 dB
	Maximum	-	1.1 dB
Change in insertion loss over T	Maximum	0.2 dB	0.2 dB
Change in insertion loss over λ	Maximum	0.2 dB	0.2 dB
Polarization dependent loss	Maximum	0.1 dB	0.1 dB
Polarization mode dispersion	Maximum	0.1 ps	0.1 ps
Number of pump lasers		4	4
Environmental			
Power dissipation, BOL	Typical	40 W	40 W
	Maximum	70 W	70 W
Operating case temperature		-5 to 70 °C	-5 to 70 °C
Storage temperature		-40 to 85 °C	-40 to 85 °C
Typical Performance			
Gain in SMF-28		10 to 12 dB	11 to 13 dB
Gain in LEAF		15 to 17.5 dB	14 to 16.5 dB
Gain in TW-RS		17 to 19 dB	19 to 22 dB
Effective noise figure in SMF-28		-0.1 to -0.9 dB	-0.5 to -1.7 dB
Effective noise figure in LEAF		-1 to -2.1 dB	-1.1 to -2.7 dB
Effective noise figure in TW-RS		-1.2 to -2.2	-1.6 to -3.3 dB

Fibre amplifier summary

	Er-doped	Raman
Gain	20 to 25 dB	10 dB
Bandwidth	32 nm	32 nm
Flatness	1 dB	1 dB
O/P power	100 mW	500 mW
System power	60W	90W
Noise figure	5.5 dB	0 dB