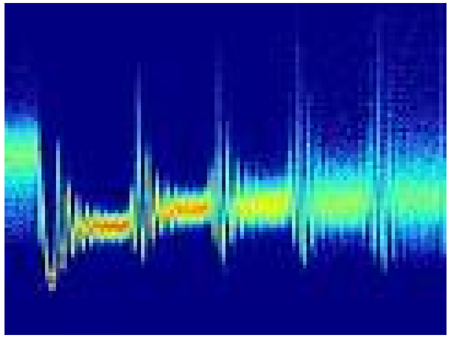
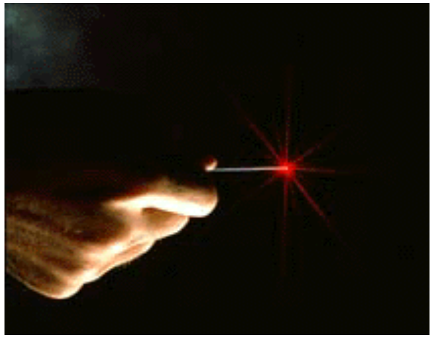
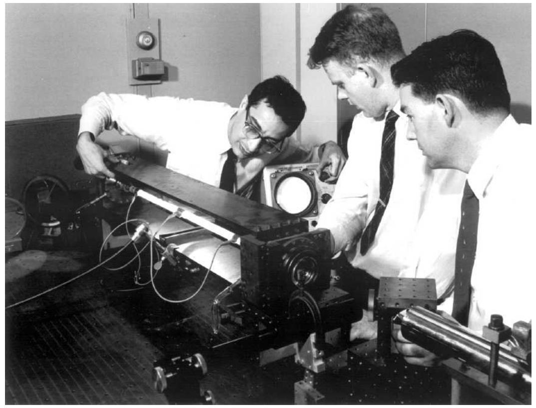
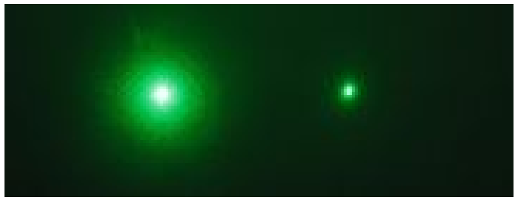
Chapter 1

Basics of Semiconductor Lasers









History

Charles H. TOWNES

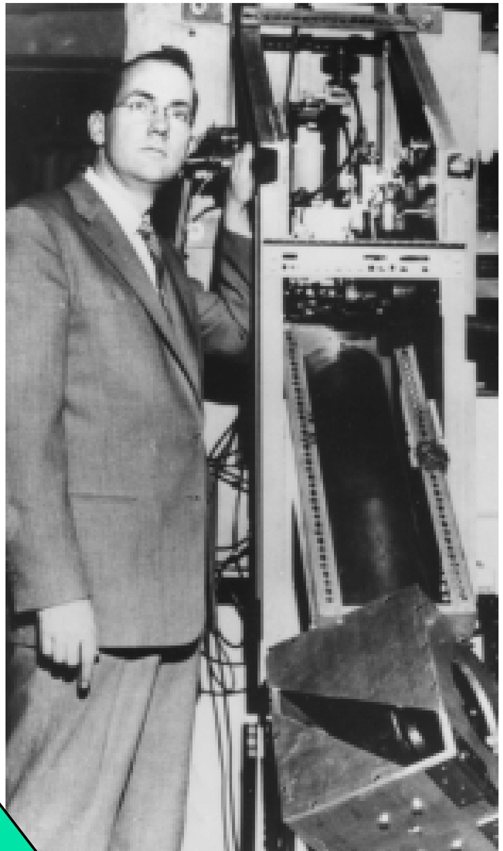
Arthur L. SCHAWLOW

Theodore MAIMAN

- **1960**: Schawlow & Townes (Bell Labs, US) patented the concept
- Maiman (Hughes Aircraft) constructed the **first ruby laser**
- **1964**: Townes, A. Prokhorov et N. Basov (Lebedev Institute, URSS) won the Nobel Prize for their contributions on LASERS

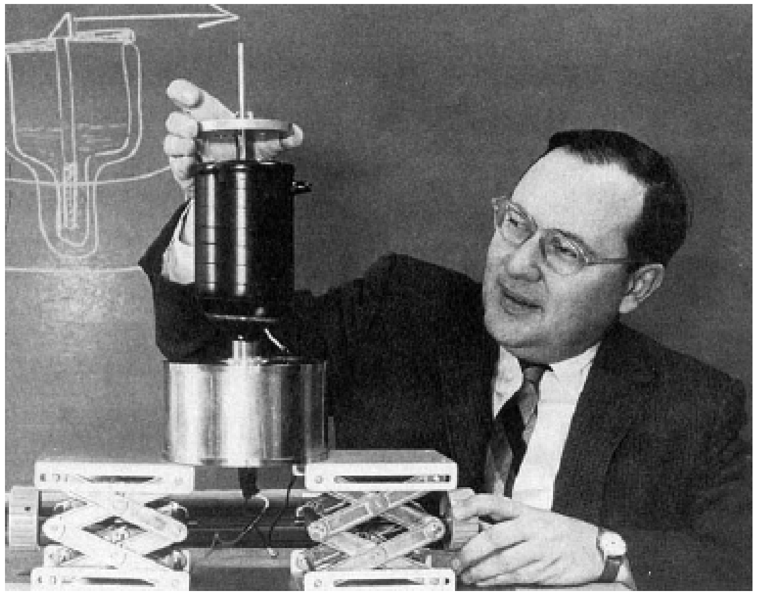
Light Amplification by Stimulated Emission of Radiation

What is a LASER?

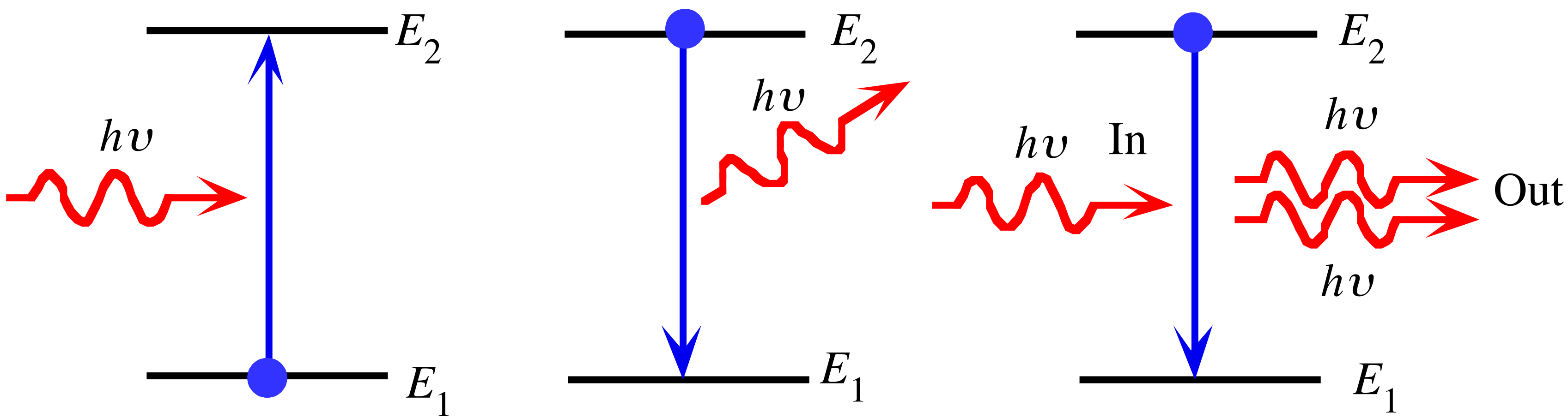


Charles H. Townes in 1957 standing next to his ruby maser amplifier for radio astronomy

Arthur L. Schawlow in 1961 with a ruby laser built by his Stanford group. The solid state laser was a dark ruby crystal containing Cr^{3+} ions. Lasing is obtained by stimulated emission from the Cr^{3+} ions



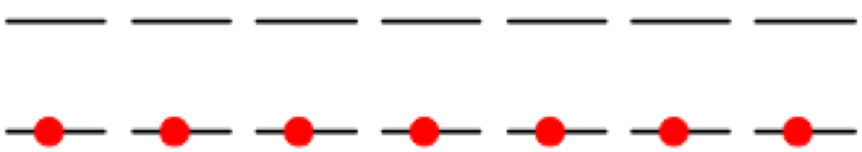
Basic Process (I)



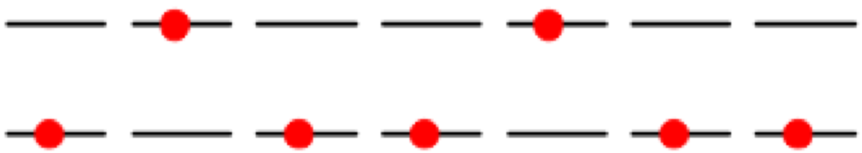
- Absorption
- Spontaneous emission (electron may spontaneously decay to the ground state ⇒ **random photons**)
- Stimulated emission (**coherent photons**)

Basic Process (II)

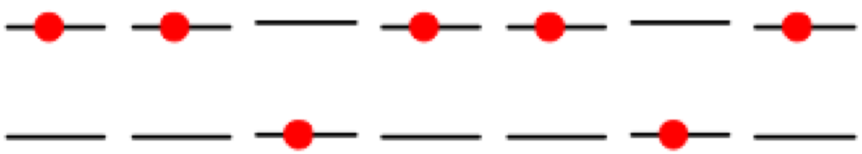
AMPLIFICATION OPTIQUE ET INVERSION DE POPULATION



$$\alpha = \sigma_{op} N_i$$

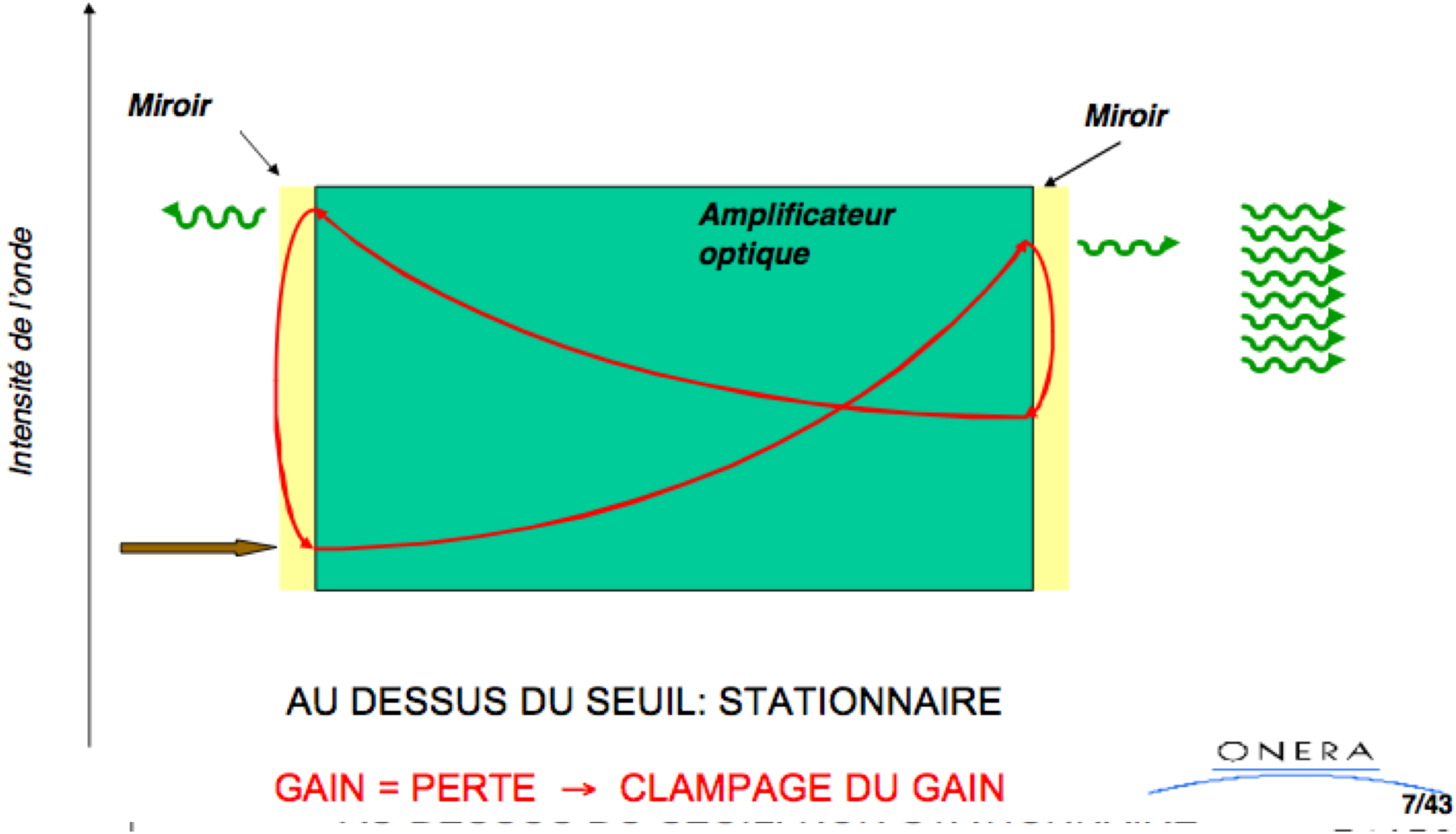


$$\alpha = \sigma_{op} \left(N_i - N_f \right)$$

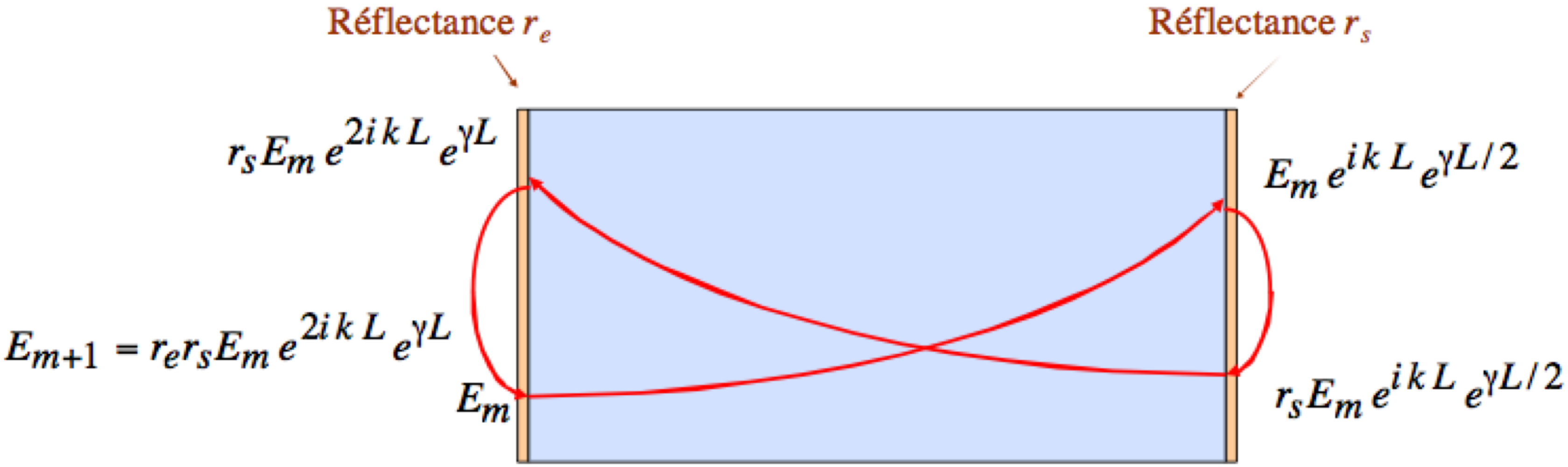


$$\gamma = -\alpha = \sigma_{op} \left(N_f - N_i \right)$$

Basic Process (III)



CONDITIONS D'OSCILLATION LASER (1)



Etat stationnaire: $E_{m+1} = E_m$

Condition d'oscillation laser: $r_e\, r_s\, e^{\gamma L}\, e^{i2kL} = 1$

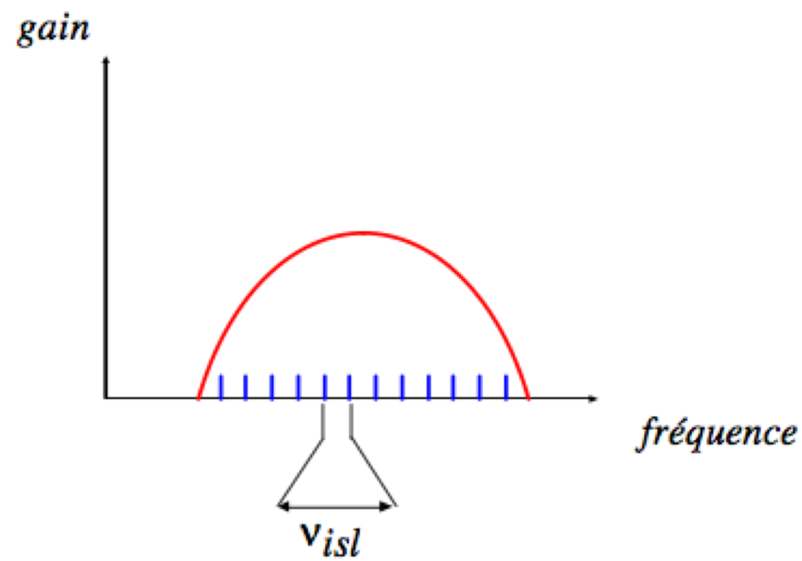
CONDITIONS D'OSCILLATION LASER: PHASE (2)

Condition sur la phase $2kL = 2m\pi$

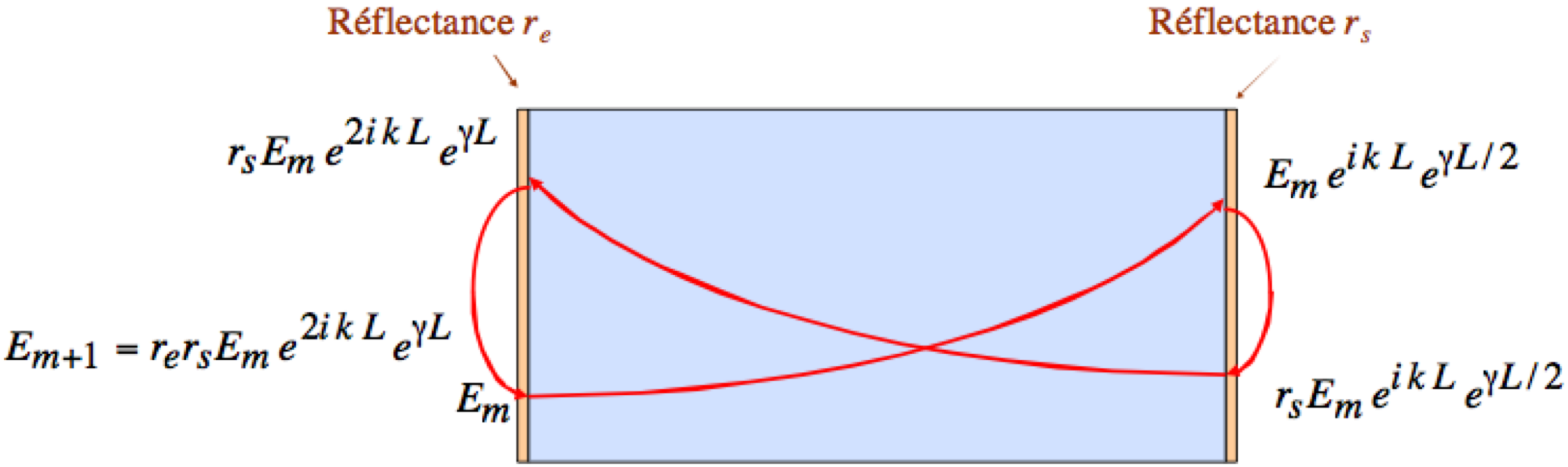
$$\omega = 2\pi\nu = k\frac{c}{n_{op}}$$

$$\Rightarrow \nu_m = m\frac{c}{2Ln_{op}} = m\nu_{isl}$$

ν_{isl} *Intervalle spectral libre*



CONDITIONS D'OSCILLATION LASER (1)



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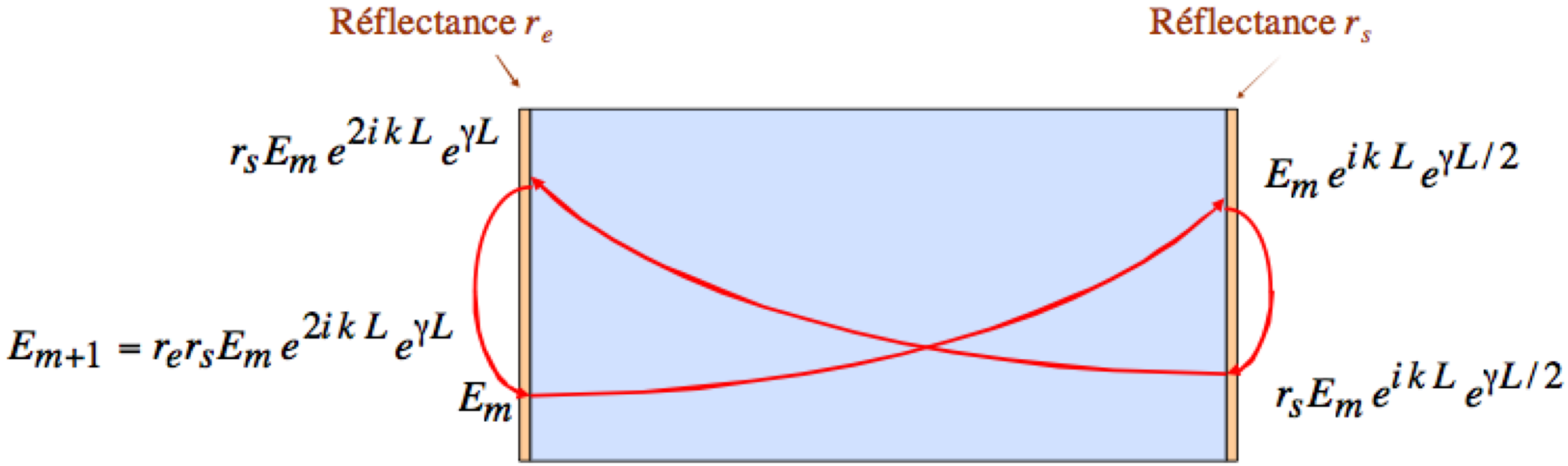


Etat stationnaire: $E_{m+1} = E_m$

Condition d'oscillation laser: $r_e\, r_s\, e^{\gamma L}\, e^{i2kL} = 1$

CONDITIONS D'OSCILLATION LASER: AMPLITUDE (2)

Condition sur l'amplitude: $r_e r_s e^{(\gamma - \alpha_p)L} = 1$

Absorption parasite

Il y a oscillation laser dès que les gains contrecarrent exactement les pertes

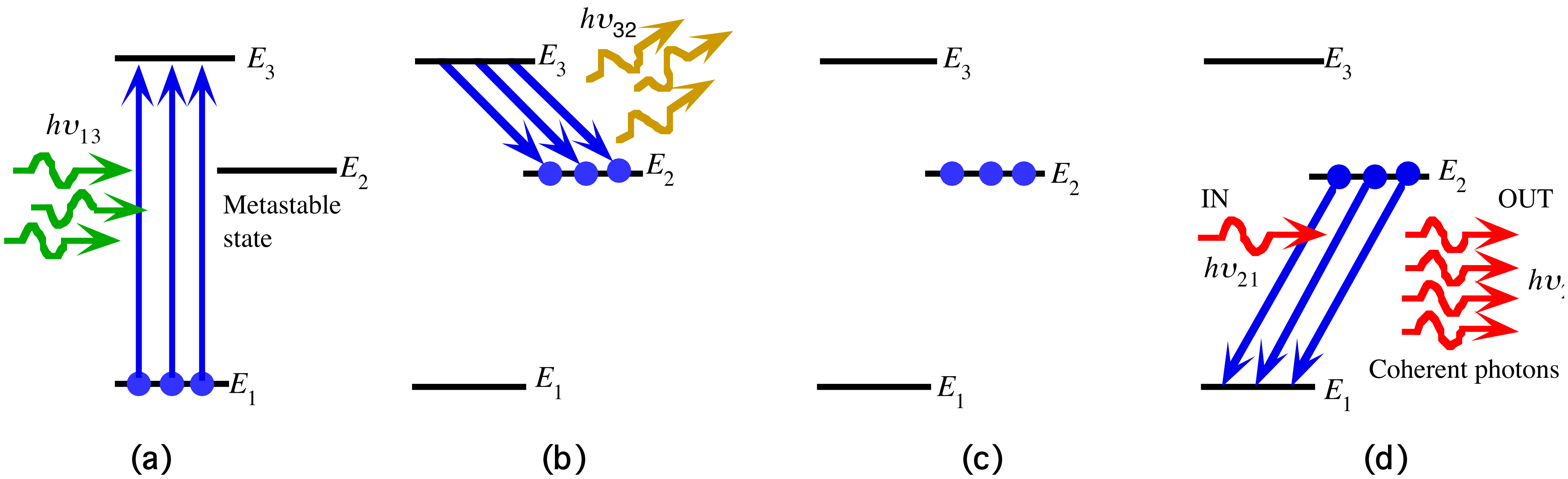
$$\gamma_s = \alpha_p + \frac{1}{2L}\ln\left(\frac{1}{R_e R_s}\right) = \alpha_p + \alpha_m$$

Tant que $\gamma < \gamma_s$ pas d'oscillation laser

$\gamma == \gamma_s$ ⟹ Oscillation laser

A l'état stationnaire, le gain ne peut excéder les pertes: Le gain est *clampé* à sa valeur seuil

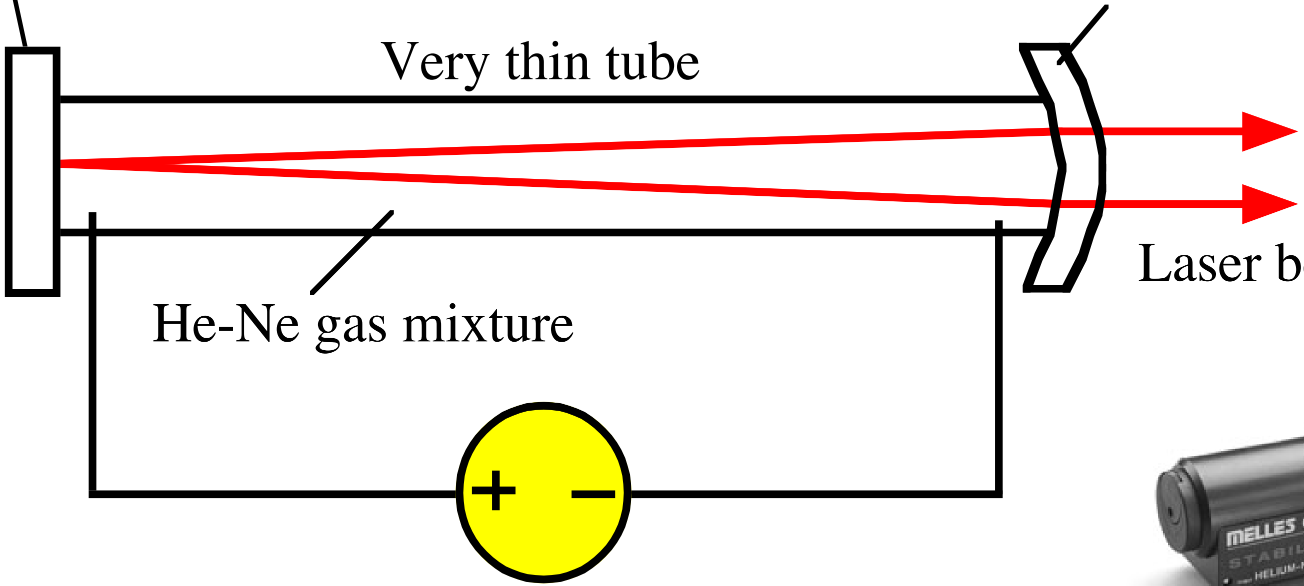
Remarque utile: $R_e = R_s = 1 - T$ ⟹ $\alpha_m \approx \frac{T}{L}$



The principle of the LASER. (a) Atoms in the ground state are pumped up to the energy level E_3 by incoming photons of energy $h\upsilon_{13} = E_3–E_1$. (b) Atoms at E_3 rapidly decay to the metastable state at energy level E_2 by emitting photons or emitting lattice vibrations; $h\upsilon_{32} = E_3–E_2$. (c) As the states at E_2 are long-lived, they quickly become populated and there is a population inversion between E_2 and E_1.

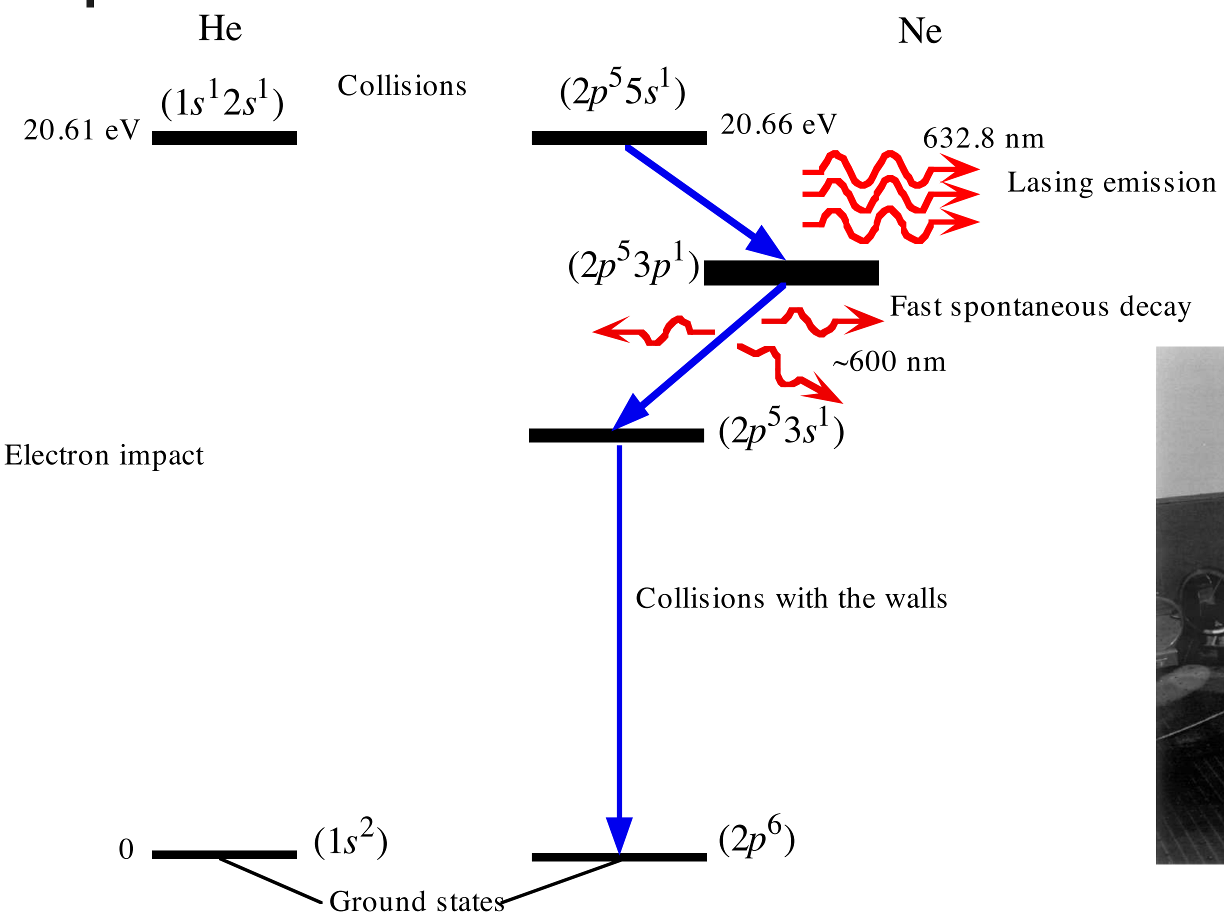
(d) A random photon (from a spontaneous decay) of energy $h\upsilon_{21} = E_2–E_1$ can initiate stimulated emission. Photons from this stimulated emission can themselves further stimulate emissions leading to an avalanche of stimulated emissions and coherent photons being emitted.

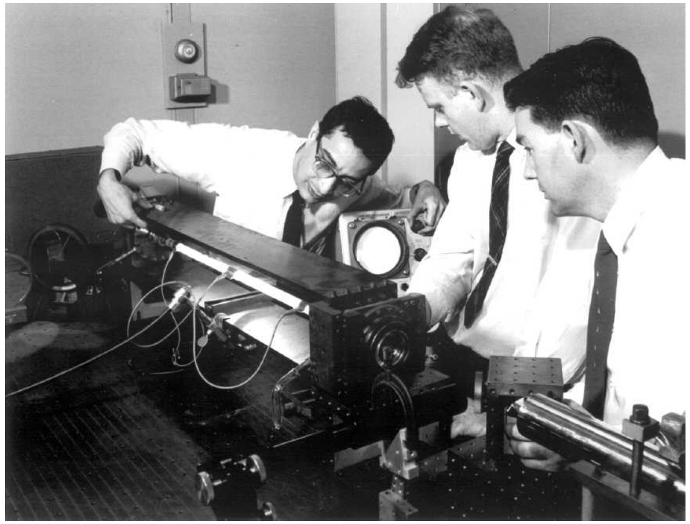
Gas Laser



A schematic illustration of the He-Ne laser

Gas Laser



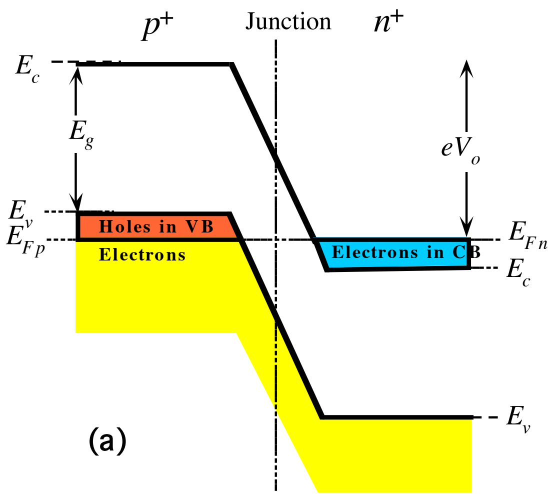


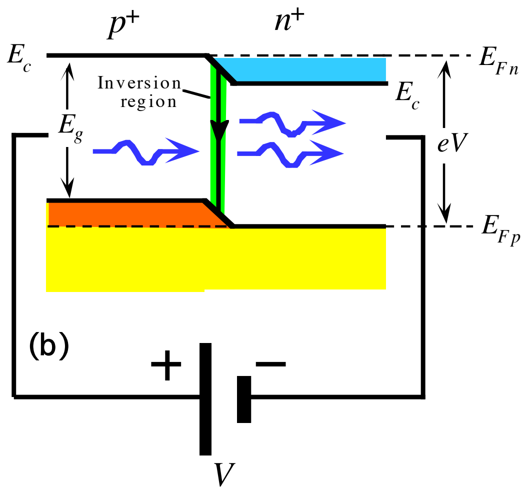
The principle of operation of the He-Ne laser. He-Ne laser energy levels (for 632.8 nm emission).

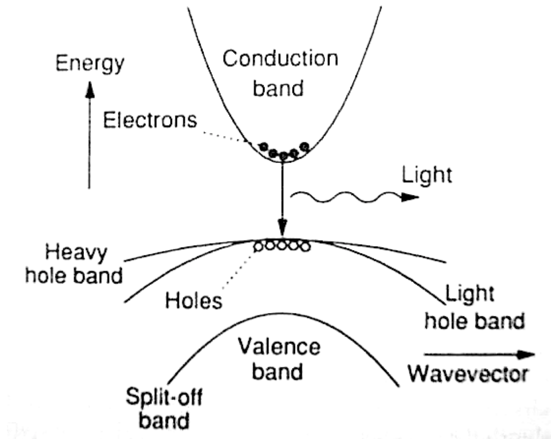
Laser Diode

- ❑ The quantum electronics concepts common to all lasers are combined in the semiconductor laser with a **pn junction** that is typical of many semiconductor devices
- ❑ Semiconductor laser action relies upon the **inter-band recombination of charge carriers (electrons and holes) and the subsequent liberation of photons**
- ❑ Forward bias makes possible **a diffusion and drift of carriers across the junction**
- ❑ In a narrow depletion region, **electron-holes pairs can recombine either radiatively or nonradiatively**
- ❑ When the current through the junction exceeds a critical value, a **population inversion** is achieved and the rate of photon emission due to carrier recombination exceeds the rate of absorption due to carrier generation

Band Diagram

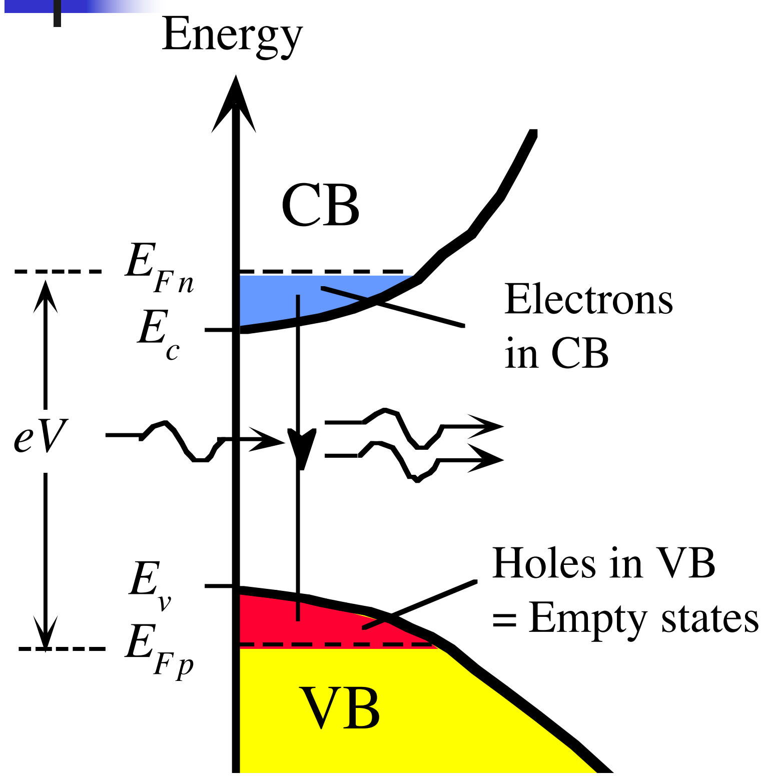


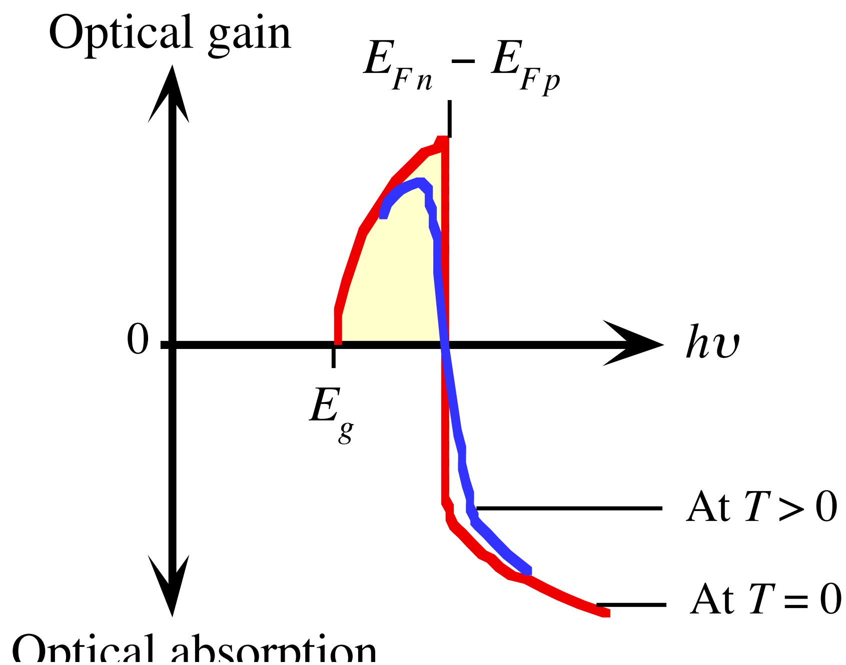




- Radiative transition takes place between **the conduction and valence bands**
- Optical transitions are between a **continuous band of states within the valence and conduction bands**
- **Higher concentration of electronic states** in the bands ⇒ potential for higher optical gain in a diode laser
- Excited eh pairs are transported through the material by conduction or diffusion leading to a spatial variation of the optical mode through the stimulated emission

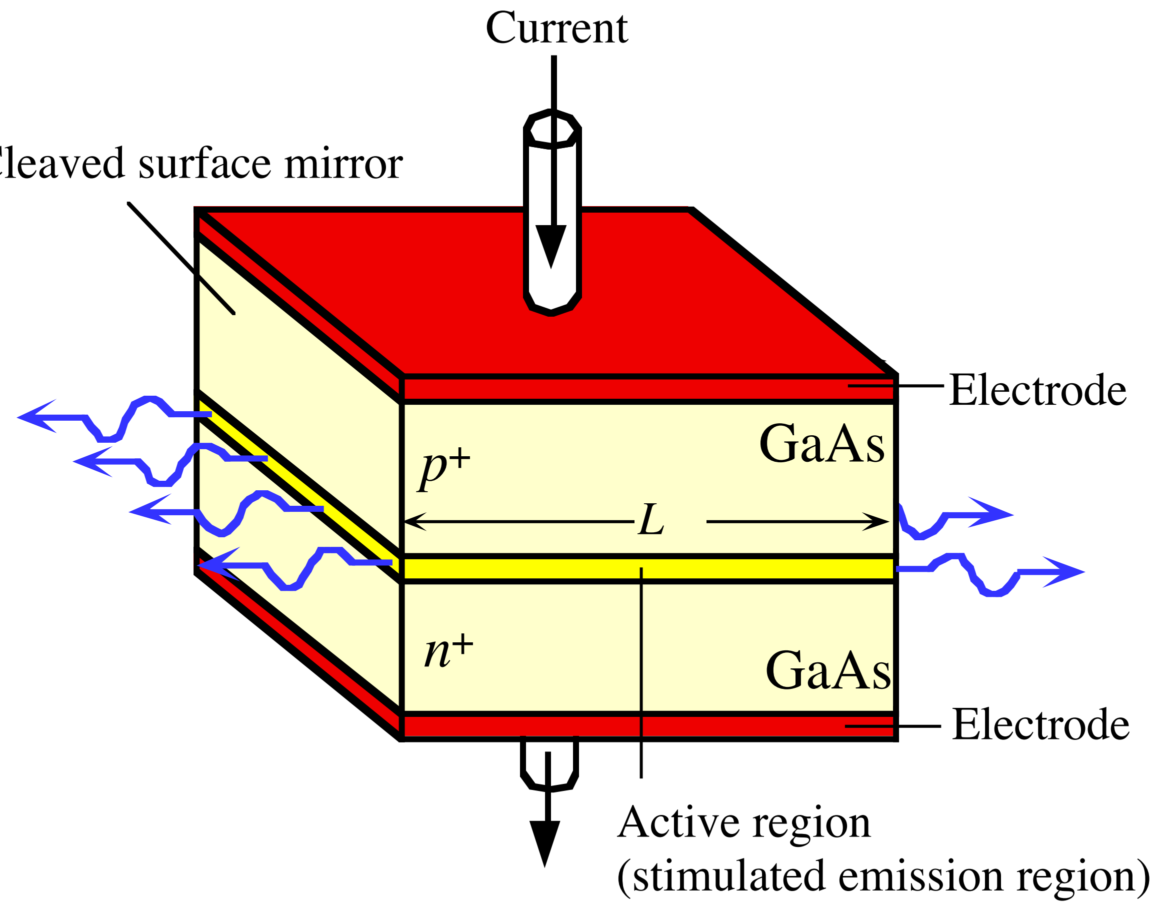
Band Diagram





- The transition from the conduction band to the valence one should be radiative and yield a photon with energy $h\nu=E_2-E_1$
- Conservation of both the energy and wave vector
- **Direct band-gap semiconductors** required for radiative recombination
- Net stimulated emission or optical gain: $E_{fn}-E_{fp}> h\nu$
- This condition is necessary, but not sufficient: to achieve lasing, **the stimulated emission rate must be sufficient to overcome various loss mechanisms**

Homojunction



A schematic illustration of a GaAs homojunction laser diode. The cleaved surfaces act as reflecting mirrors.

Optical Gain

- Optical gain is obtained by assuming a **linear dependence on carrier concentration and a parabolic variation with wavelength**

$$g = g_0(N - N_t) + b(\lambda - \lambda_p)$$

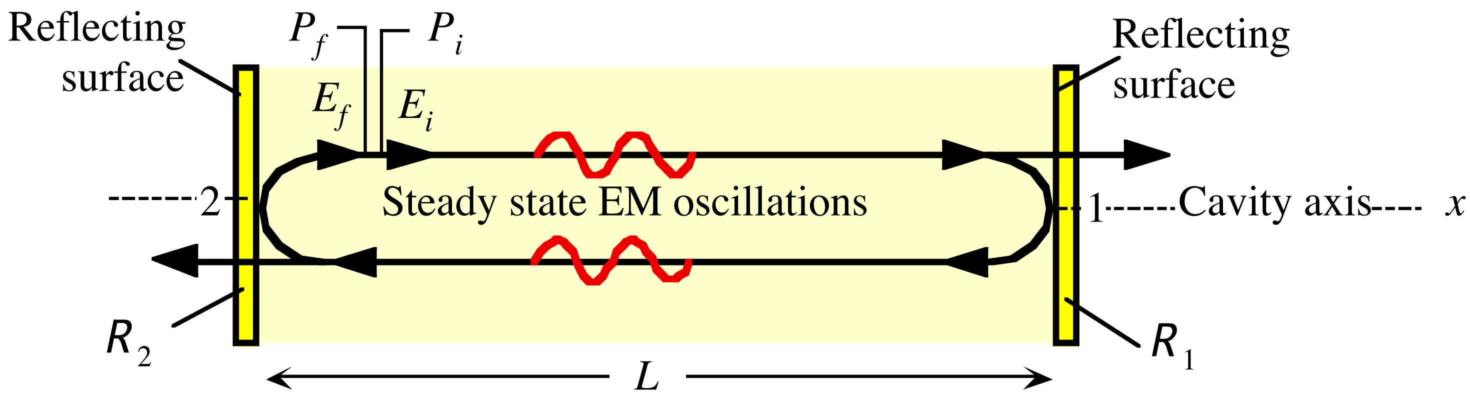
g_0 is the differential gain, N is the transparency density for which g=0 at $\lambda=\lambda_p$ and $N=N_t$, b is related to the gain spectral width, and λ_p is the wavelength corresponding to the gain peak

- As the carrier concentration is supposed to increase due to the current injection, **the photon energy at the gain peak shifts to higher values**

$$\lambda_p = \lambda_0 + (N - N_t)\frac{d\lambda}{dN}$$

- Above parameters can be obtained from gain measurements
- InGaAsP lasers: λ_0=1550 nm, g_0=2.7 10^{-16} cm^2, b=0.15 cm^{-1} nm^{-2}, N_t=1.2 10^{18} cm^{-3} and $d\lambda \backslash dN$=-2.7 10^{-17} nm cm^3

Laser Cavity



- The optical gain alone is not enough to operate a laser
  ⇒ Optical feedback needed ⇒ cleaved facets act as partially reflecting mirrors
- The laser cavity provides a direction selectivity for the process of stimulated emission
- Photons traveling along its axis are **reflected back and forth and experience maximum gain**
- It also provides a frequency selectivity since the feedback is strongest for frequencies corresponding to the modes of the Fabry-Perot cavity

Threshold

❑ Although spontaneous and stimulated emission can occur while current is applied, the laser does not generate coherent emission until the current exceeds a critical value, **threshold current**

❑ **Threshold conditions: the optical field in the cavity reproduce itself after each round trip** (continuous-wave conditions)

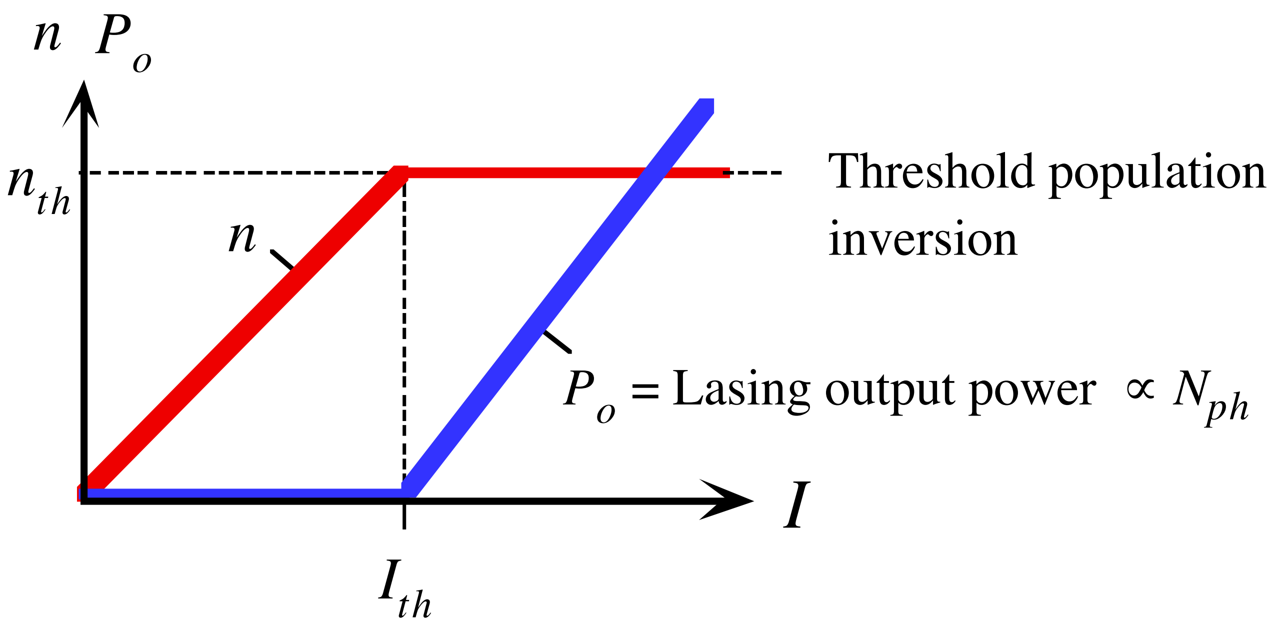
$$\Gamma g_{th} = \alpha_i + \frac{1}{2L}\ln(\frac{1}{R_1 R_2})$$

$$\beta L = m\pi$$

m is an integer, g_{th} the threshold gain, α_i the internal loss in the active layer due to free-carrier absorption and scattering, L the cavity length, R_1 and R_2 the facet reflectivities and β the propagation constant

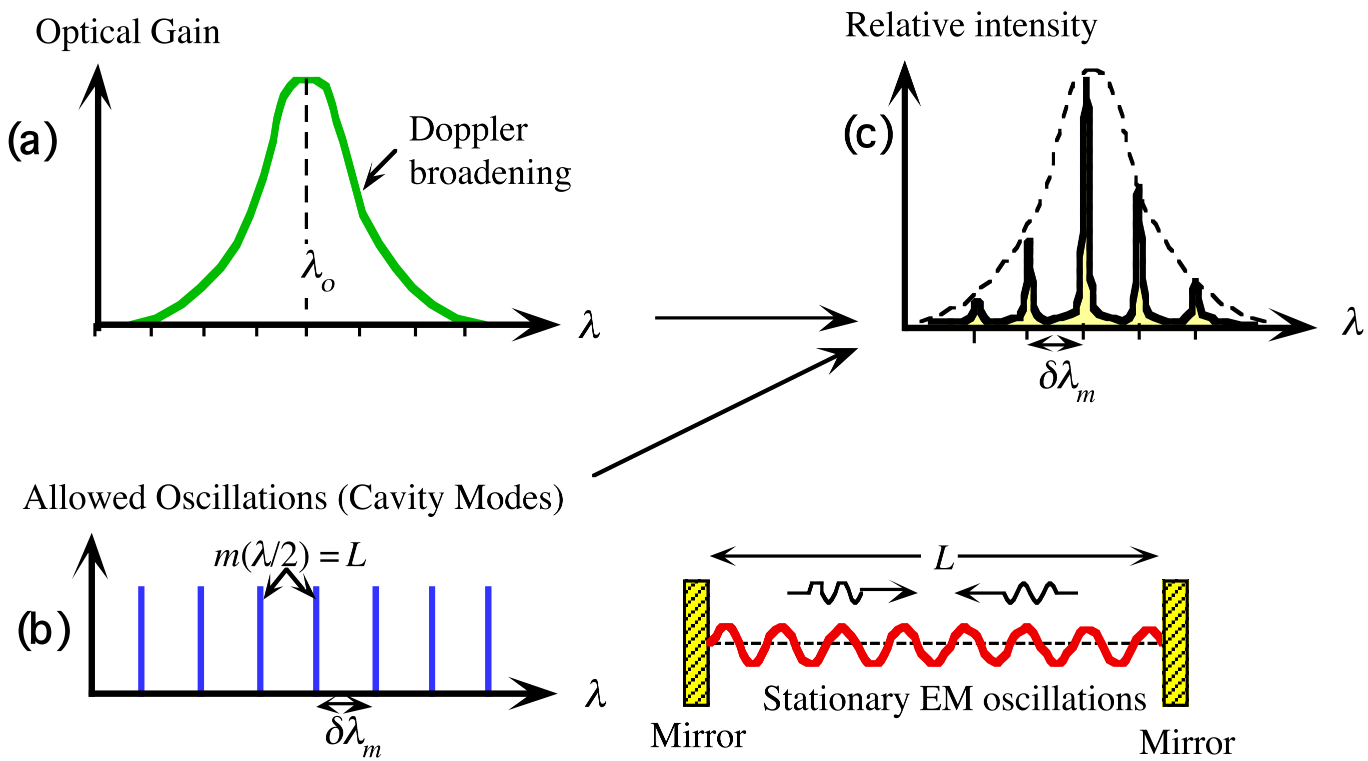
❑ The factor Γ is the **optical confinement** representing the fraction of the mode energy contained in the active layer i.e **spreading of the optical mode to the cladding layers surrounding the active layer**

Threshold



Simplified and idealized description of a semiconductor laser diode based on rate equations. Injected electron concentration n and coherent radiation output power P_o vs. diode current I.

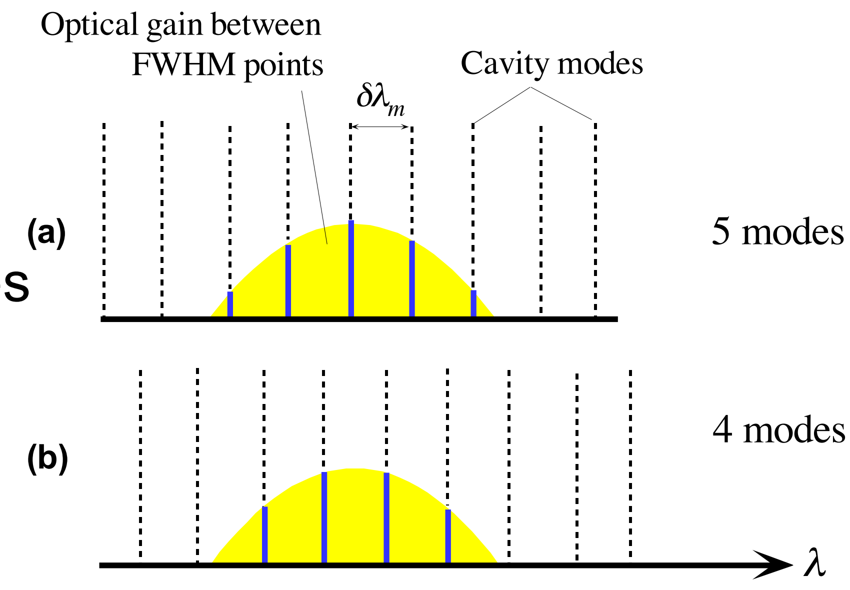
Optical Gain



(a) Optical gain vs. wavelength characteristics (called the optical gain curve) of the lasing medium. (b) Allowed modes and their wavelengths due to stationary EM waves within the optical cavity. (c) The output spectrum (relative intensity vs. wavelength) is determined by satisfying (a) and (b) simultaneously, assuming no cavity losses.

Laser Modes

- Lasing frequency ω_m is the **nearest to the gain peak**
- The refractive index n varies with the frequency (material dispersion)
- The gain bandwidth of semiconductor lasers is very broad as compared to the FSR ⇒ **multi-longitudinal mode operation**
- **Several modes meet the phase condition** and exhibit gains slightly smaller than the threshold gain



$$\omega_m = \frac{m\pi c}{nL}$$

$$n_g = n + \omega \frac{\partial n}{\partial \omega}$$

Roundtrip time

$$\delta\tau = \frac{2\pi}{\delta\omega} = \frac{2n_g L}{c}$$

Free Spectral Range

$$\delta\omega = \frac{\pi c}{n_g L}$$

Laser LCC

- The interband radiative recombination leads to either spontaneous or stimulated emission
- The electron-hole recombination rate R(N) can be written such as:

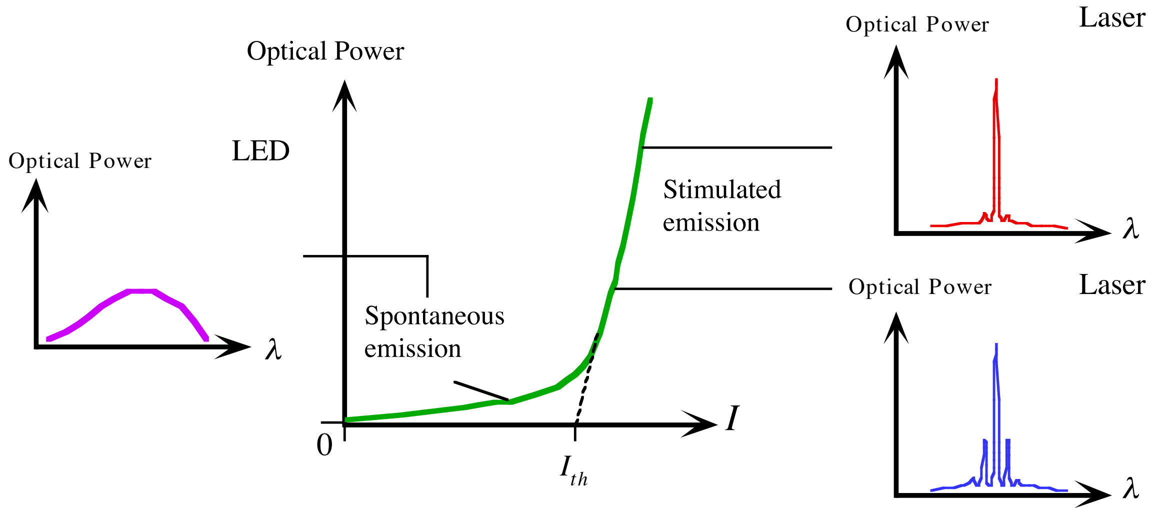
$$R(N) = AN + BN^2 + CN^3 + R_{st}N_{ph}$$

where R_{st} describes the **net rate of stimulated emission**, N_{ph} is the intracavity photon density and A, B, and C are the **parameters of spontaneous recombination**

- The cubic term CN^3 referred to as **Auger recombination** whose inclusion is of first importance for long-wavelength diode lasers
- The **bimolecular coefficient** B is know to be dependent on N and is often approximated by $B=B_0-B_1N$
- The **stimulated emission term** is directly proportional to the optical gain,

$$R_{st} = \frac{c}{n_g} g(N)$$

Laser LCC



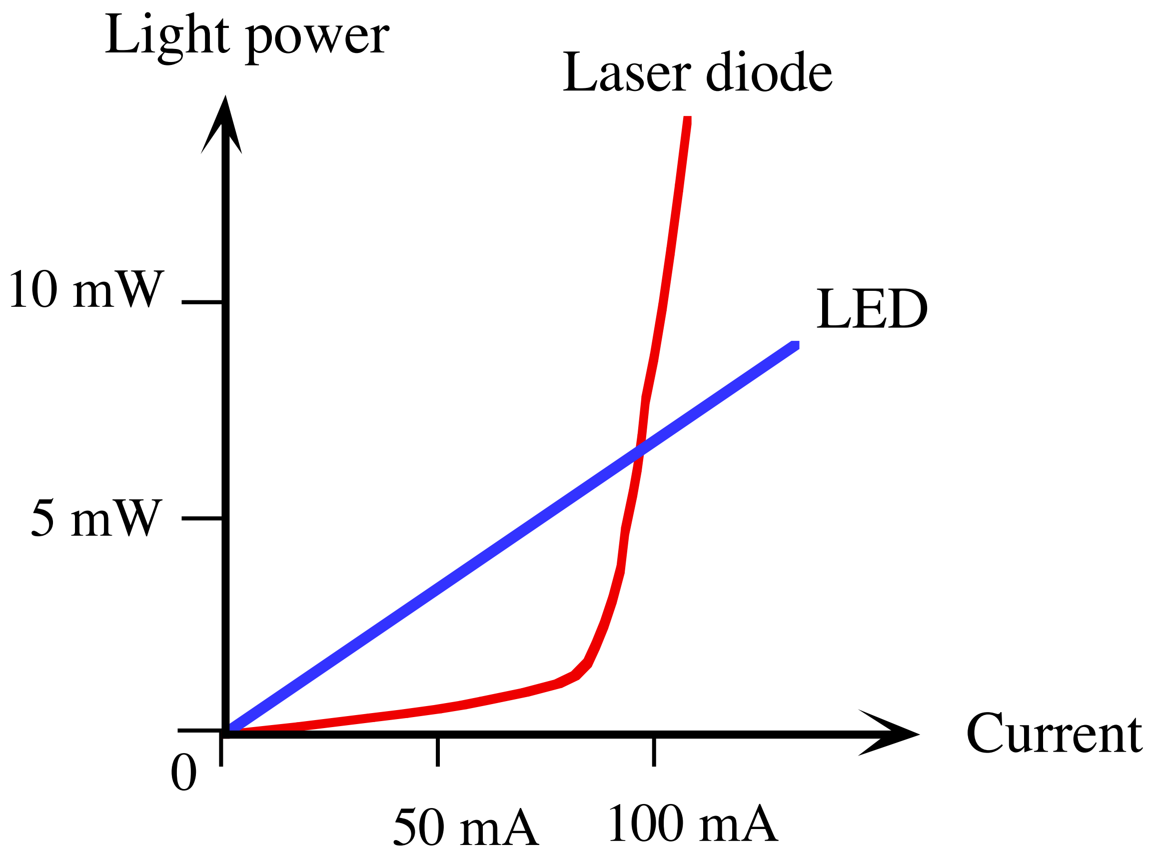
❑ Assuming a **linear dependence of the optical gain on the carrier** concentration, the ideal light-current characteristics (LCC) above the laser threshold is

$$P(I) = \frac{\hbar\omega}{2e} \frac{\alpha_m}{\alpha_m + \alpha_i}(I - I_{th}) \qquad \alpha_m = \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$ **Mirror loss**

❑ The slope of the curve is reasonably constant until the **power saturation mechanisms settle in**

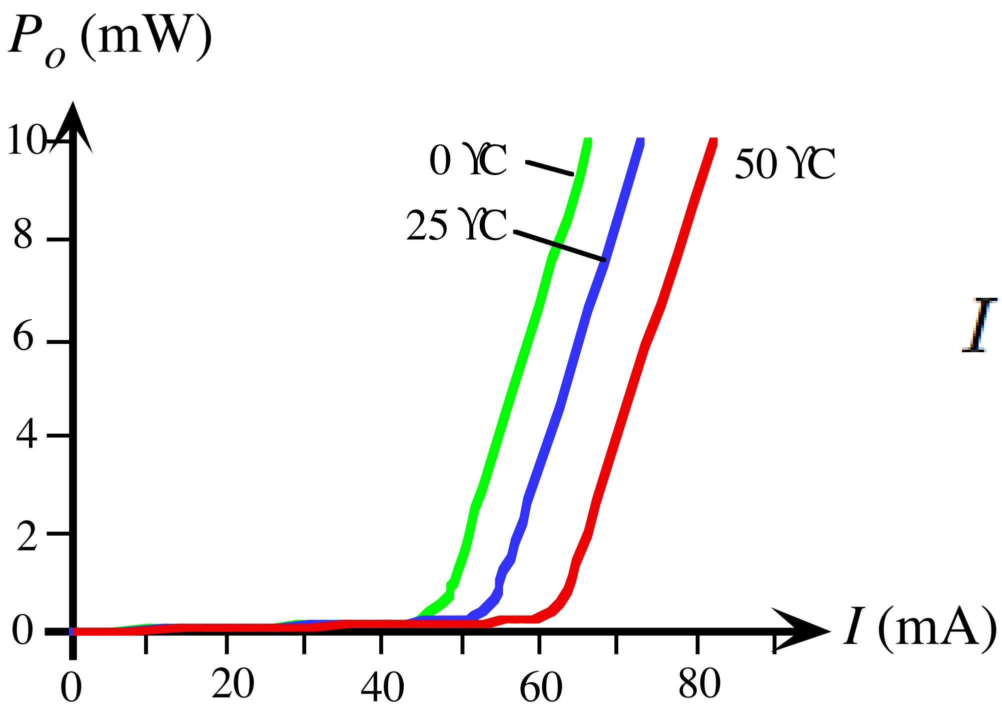
❑ Power saturation is connected with the **thermal heating** of the device

Laser vs LED



Typical optical power output vs. forward current for a LED and a laser diode.

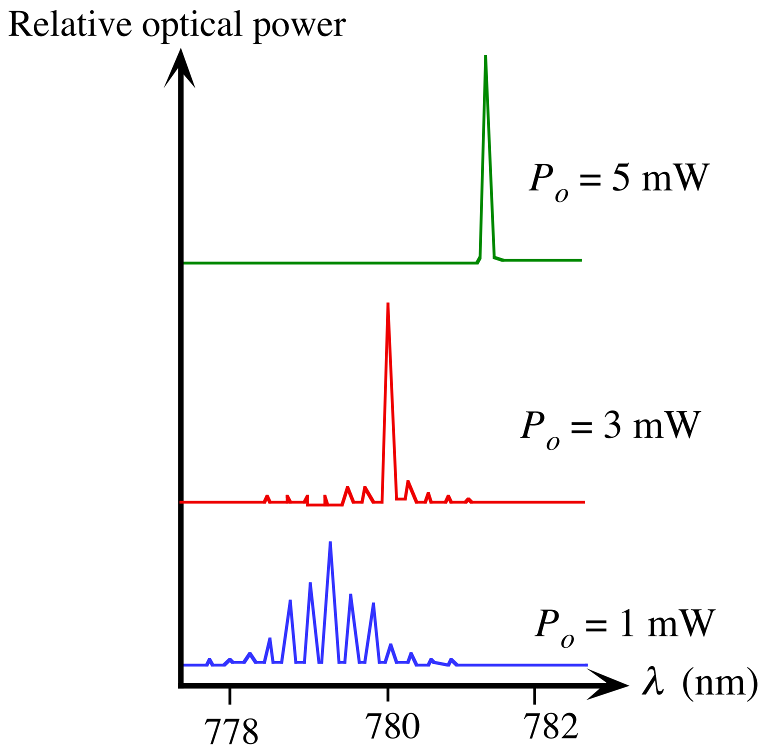
Temperature



$$I = I_{th} \exp(T/T_0)$$

- The threshold current is **temperature dependent**
- T_0 represents the **characteristic temperature**
- Typical values of T_0 are in the range of 150-200K for GaAlAs lasers and 40-70K for InGaAsP lasers

Optical Spectrum



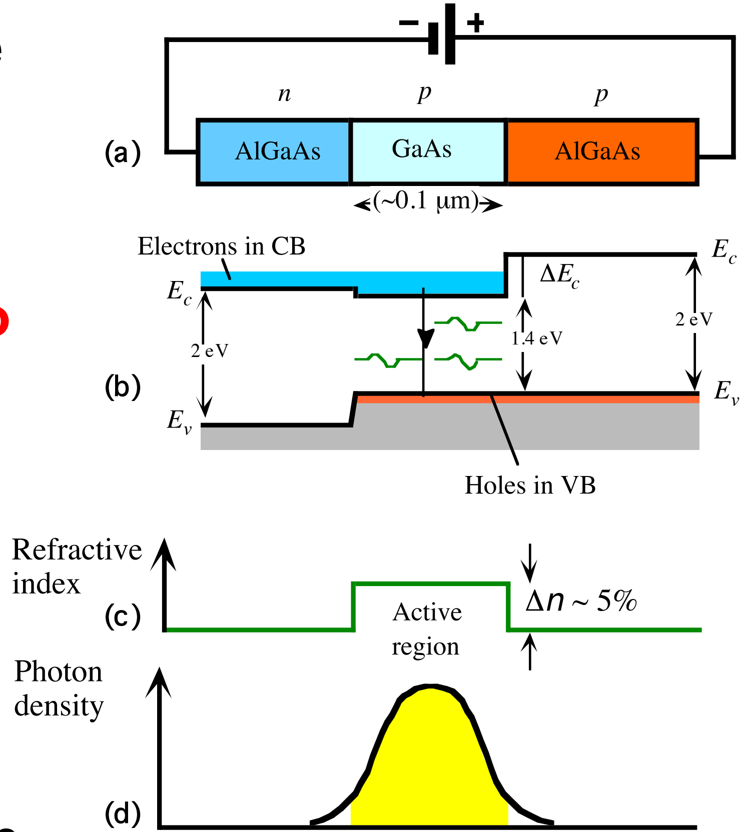
Output spectra of lasing emission from an index guided LD. At sufficiently high diode currents corresponding to high optical power, the operation becomes single mode. (Note: Relative power scale applies to each spectrum individually and not between spectra)

Heterojunction

- Although the pn junction can amplify the electromagnetic radiation and exhibits optical gain under forward bias, **the thickness of the region in which the gain is sufficiently high is very small (in the range of 0.01μm)**
- This is because **there is no mechanism to confine carriers ⇒ usually homojunctions lasers failed to operate at room temperature**
- The **carrier confinement** in the plane perpendicular to the pn junction can be achieved using **heterojunctions**
- A double heterojunction is used to prevent **electron-hole spreading from the pn junction where the carriers recombine**
- The active layer is sandwiched by two claddings layers that have **wider band gaps**
- Due to the external voltage, an injection of holes from the p-doped layer and an injection of electron from the n-doped side occur into the active layer

Heterojunction

- The potential barriers on the boundaries between the layers resulting from the band-gap differences prevent electrons and holes from **spreading into the cladding layers**
- The **concentration of minority carriers can easily reach very high values** in the active layer
- Lower current densities
- Room temperature operation and beyond



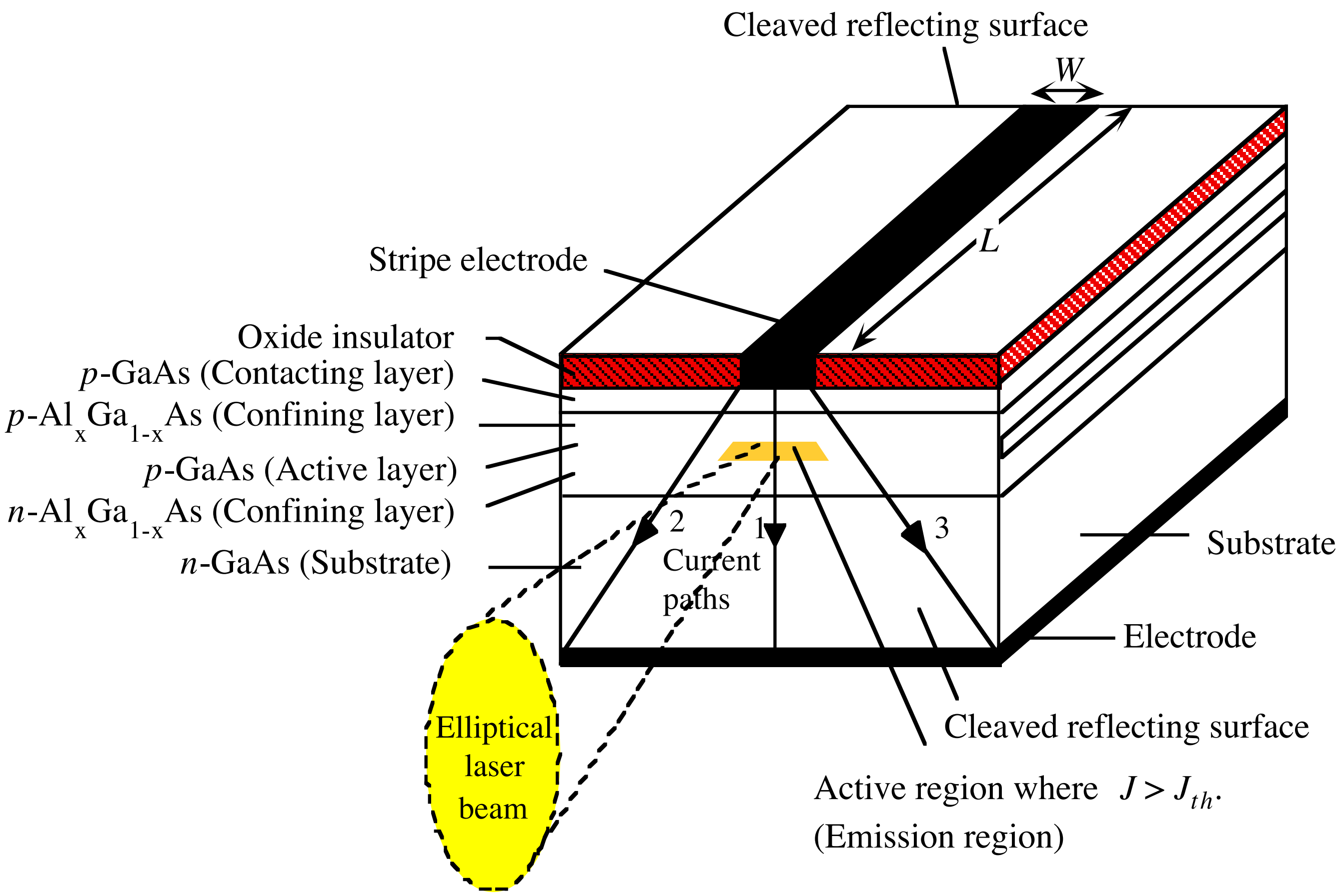
(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs).

(b) Simplified energy band diagram under a large forward bias. Lasing recombination takes place in the *p*-GaAs layer, the *active layer*

(c) Higher bandgap materials have a lower refractive index

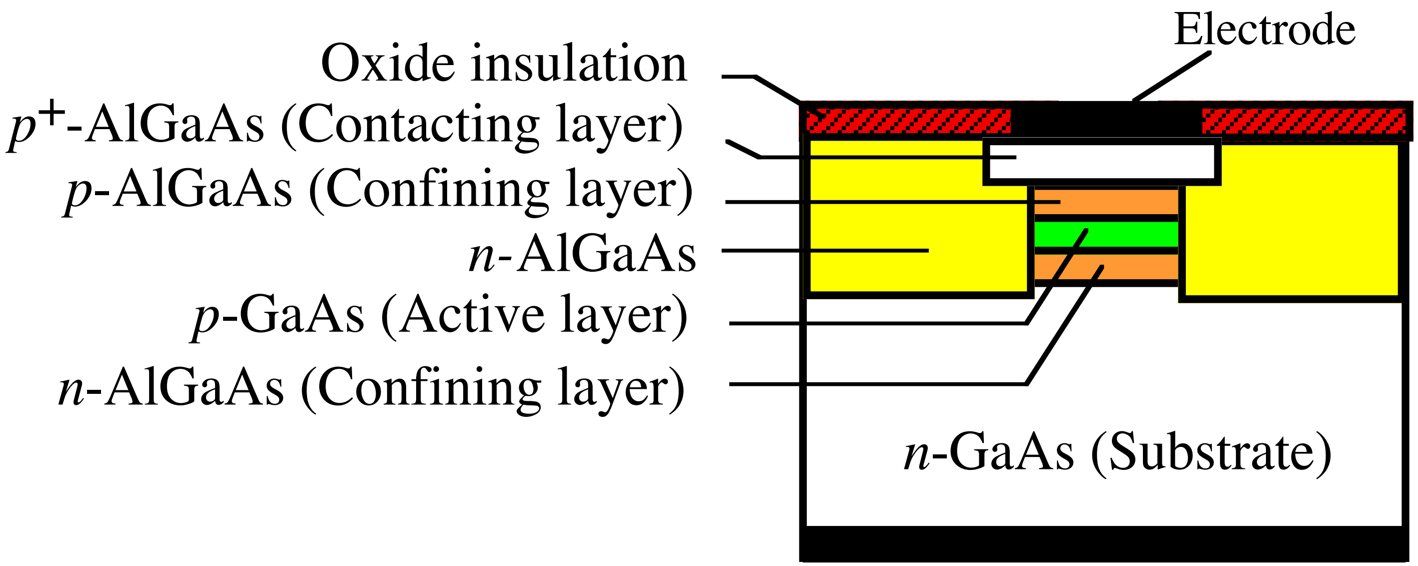
(d) AlGaAs layers provide lateral optical confinement.

Heterojunction



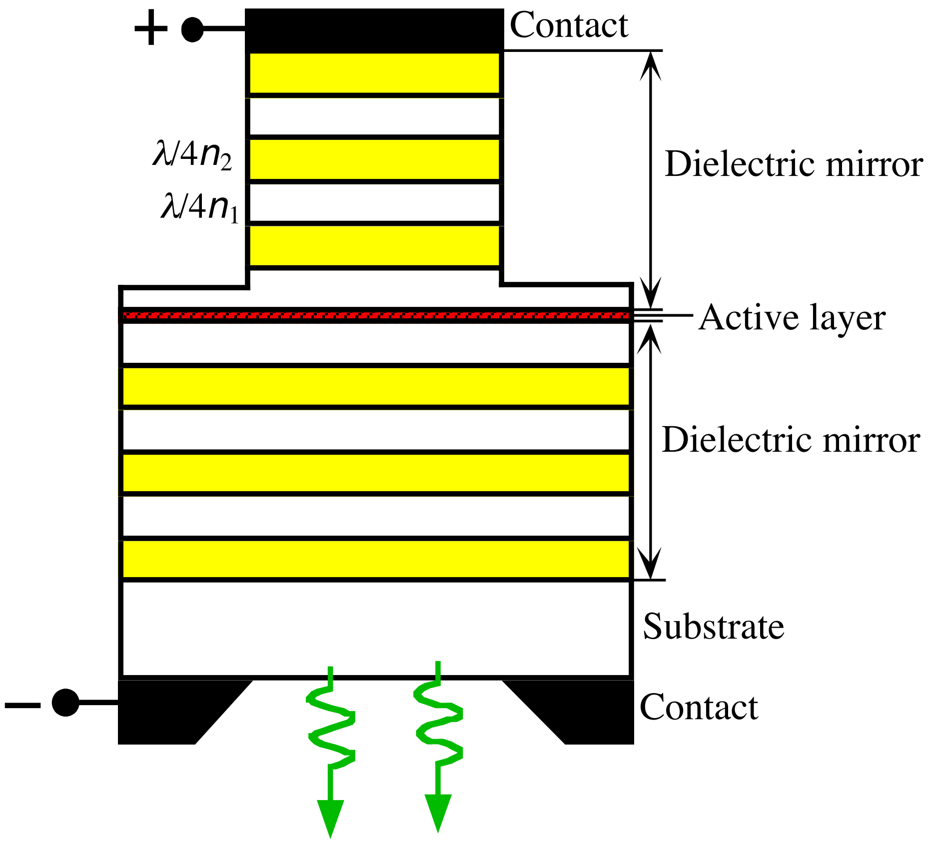
Schematic illustration of the the structure of a double heterojunction stripe contact laser diode

Heterojunction

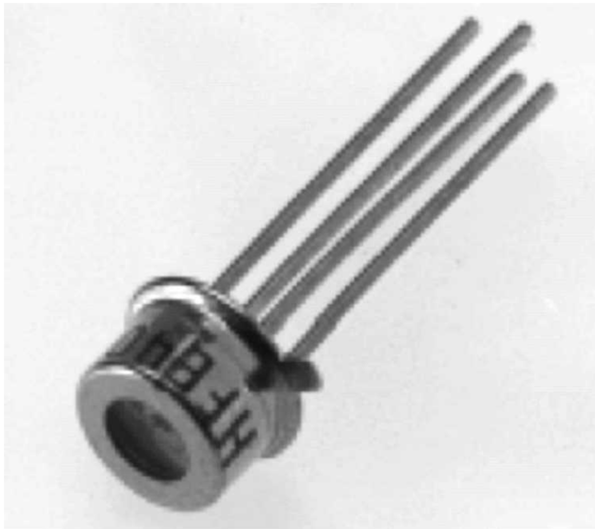


- A a **narrow stripe contact typically in the range of 2-5 μm** is required to increase the lateral confinement of carriers.
- Numerous laser structures for lateral confinement have been proposed over the years such as **buried heterostructure lasers, rib waveguide laser and ridge waveguide lasers**

VCSEL



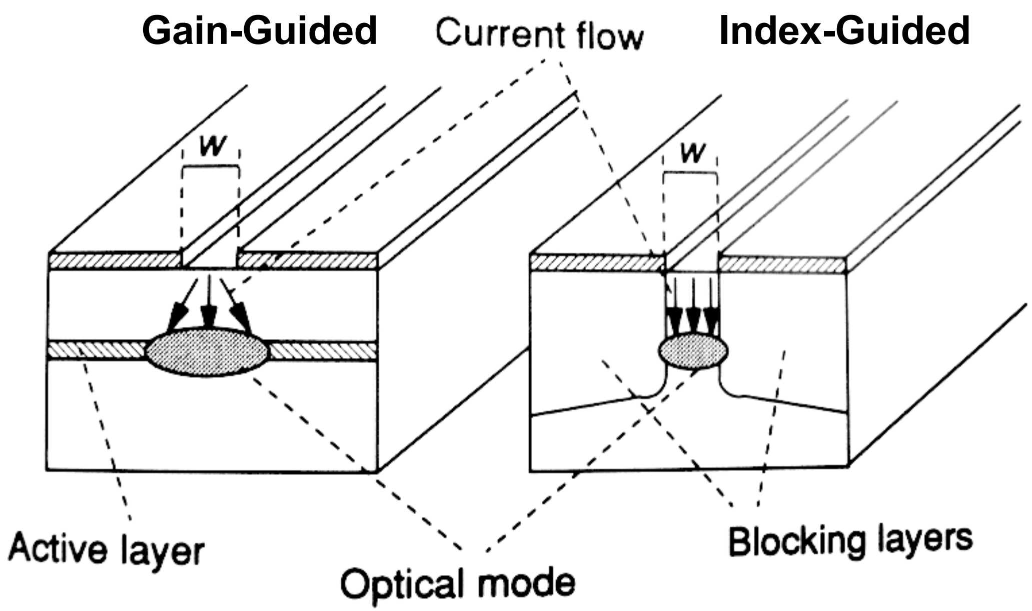
A simplified schematic illustration of a vertical cavity surface emitting laser (VCSEL).



An 850 nm VCSEL diode (Courtesy of Honeywell)

Optical confinement

- Optical confinement may also be achieved by laterally varying the effective refractive index e.g. **by changing the material composition or the shape of the waveguide**
- In the direction perpendicular to the junction plane, the refractive index discontinuity between the active and cladding layers is responsible for the optical field confinement through the **total internal reflection** occurring at the interfaces



- **Gain-guided lasers: the stripe restricts the injection of carriers in the lateral direction**
- Small variations that occur in the refractive index result in variation of gain/loss and vice versa

Optical confinement

- Wide stripes (>7 to 10μm): excitation of **higher lateral modes** can occur
- Index-guided: lateral index steps due to additional blocking layers confine the mode
- **Normalized active layer thickness**

$$D = \frac{2\pi d}{\lambda}(n^2 - n_c^2)^{1/2}$$

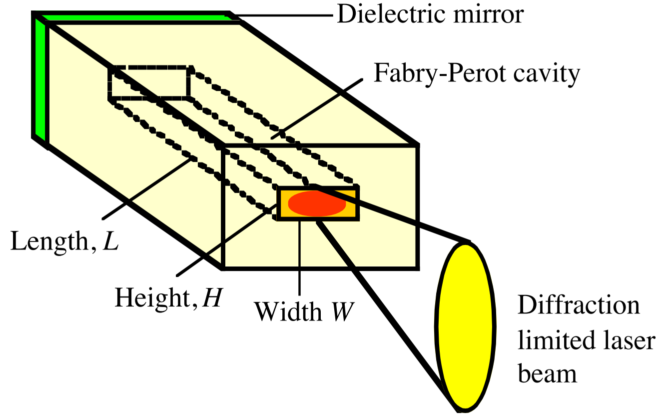
d is the true active layer thickness, n and n_c are the refractive indices of the active and cladding layers

- D decreases: the optical wave spreads into the cladding regions whereas at large values, the **optical field gets extremely well-confined**
- A useful approximation for the **transverse confinement factor Γ_T**

$$\Gamma_T = \frac{D^2}{2 + D^2}$$

- To ensure single transverse-mode behavior, D<π
- Typically d<0.2μm, **the single transverse-mode condition is satisfied**

Field Patterns



- A diode laser emits in a form of spot that has an **elliptical cross section**
- The spatial distribution of the emitted light near the facet is called as the **near field pattern**
- The angular intensity distribution far from the laser is the **far-field pattern**
- **Several spatial modes may be exited** in the structure and the resulting near- and far-fields can be seen a superposition of them
- Width and thickness of the active layer are chosen such that **only the fundamental transverse and lateral modes are supported by the waveguide**

Field Patterns

- The near-field emission pattern for a fundamental transverse mode of the symmetric slab waveguide has a FWHM

$$w_{\perp} \approx d(2\ln(2))^{1/2}(0.321 + 2.1D^{-3/2} + 4D^{-6})$$

where the normalized thickness D (usually accurate for 1.8<D<6.0)

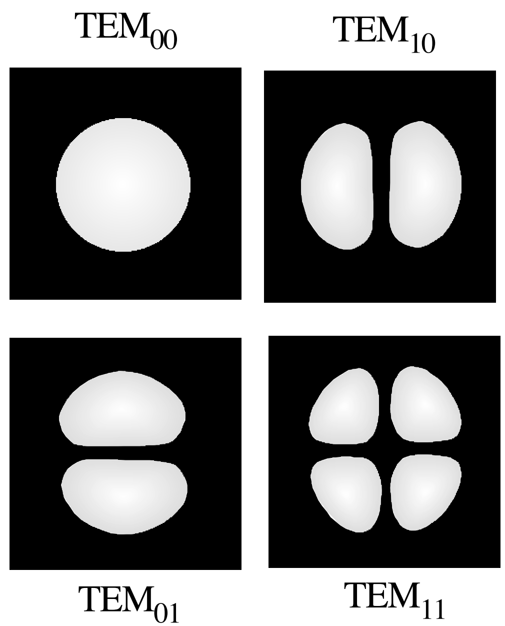
- Far-field emission pattern beamwidth:

$$\Theta_{\perp} \approx \frac{0.65D(n^2 - n_c^2)^{1/2}}{1 + 0.15(1 + n - n_c)D^2}$$

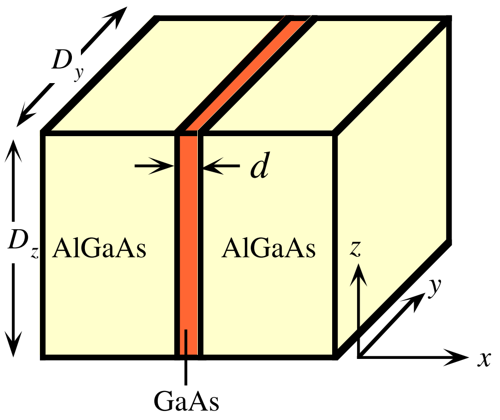
- The near-field parallel to the junction plane **depends critically on the lateral guiding mechanisms**
- **Strongly index-guided laser**: the near-field behavior in the lateral direction is similar to that for the transverse direction ⇒ **largely confined within the active layer**
- **Weakly index-guided lasers**, the lateral confinement of the optical field can be improved by varying the lateral index step

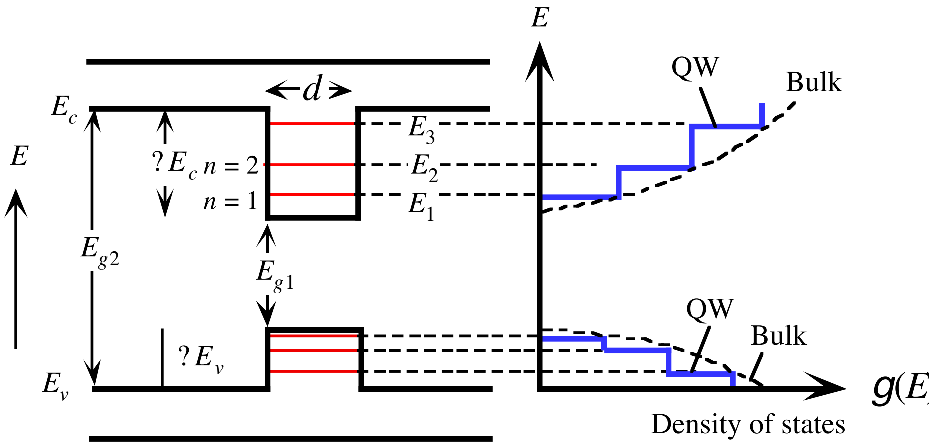
TE vs TM

- The problem of spatial modes in semiconductor laser is the problem of **modes of a slab waveguide** based upon on the solutions of Maxwell's equations
- A slab waveguide can usually support two types of modes **transverse electric (TE) or transverse magnetic (TM)**
- TE modes, the electric field is polarized along the pn junction plane while it is the magnetic field for TM modes
- In diode lasers, the **TE modes are usually favored** because the threshold gain is lower for TE-polarization due to higher facet reflectivities and a higher optical confinement factor



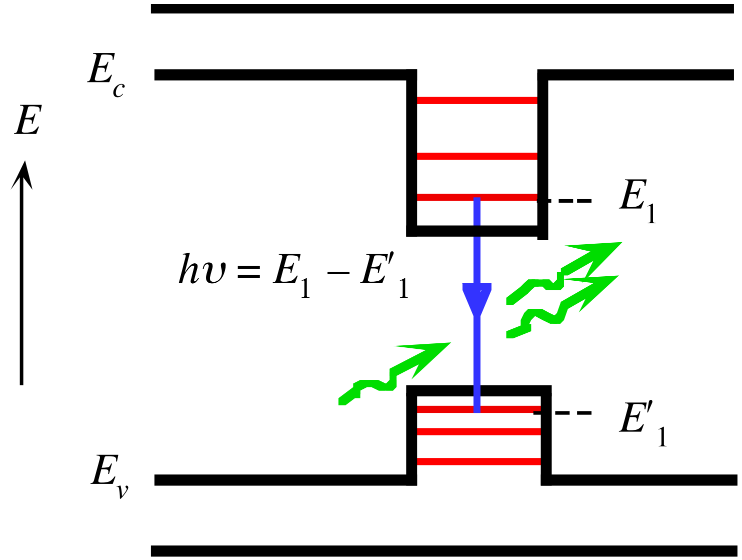
Quantum Well





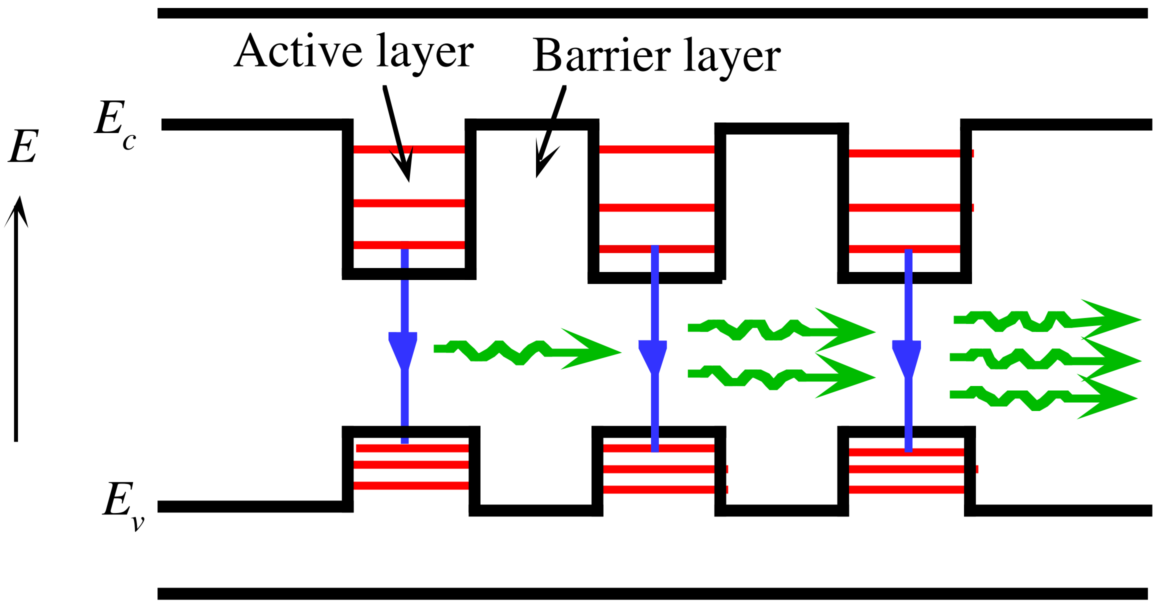
- ❑ QW lasers: thickness of the active layer reduced from 1 μm to 2-10 nm
- ❑ Active layer thickness is of the order of the de Broglie wavelength λ_D=h/p
- ❑ **Quantized motion of carriers** in the active layer for the component perpendicular to the wells
- ❑ **Quantized energy** of carriers moving in the direction of confinement
- ❑ The lowest energy radiative transition occurs at a photon energy that is significantly **higher than the band gap** of the material
- ❑ **Photon energy depends on the well width** and increases to higher values as the width decreases

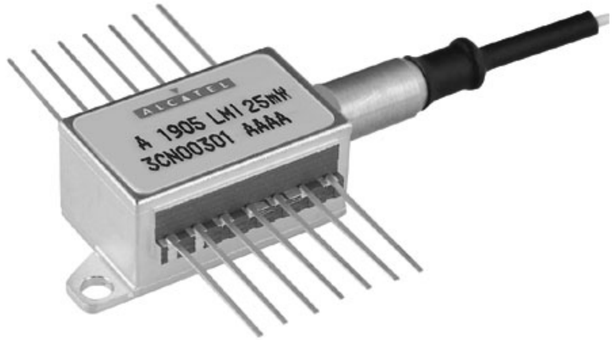
Quantum Well



- QW lasers: higher differential gain, lower threshold current densities, improved temperature performance, higher modulation bandwidths, reduced α-factor
- **Narrower optical gain spectra** (fewer lasing modes)
- If **more than one energy sub-bands** are exited, the width of the optical gain spectra can significantly exceed that of a bulk device
- Fluctuations in the well size can also lead to a **considerable broadening of the gain spectra as well as a reduction of the gain peak**

Quantum Well

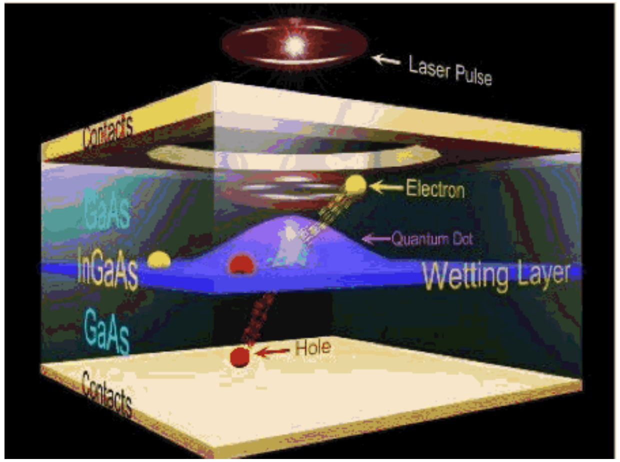




A 1550 nm MQW-DFB InGaAsP laser diode pigtail-coupled to a fiber (Courtesy of Alcatel)

- QW laser gain is also **strongly polarization-dependent**
- For narrow enough wells, **the maximum TE gain is greater** at lower energy than the gain for TM polarized light
- **Strained-layer QWs:** the lattice-mismatched QW structure can be used to design a laser with the optimal threshold condition since that strain alters the sub-band structure and optical gain of QW lasers

Quantum Dot

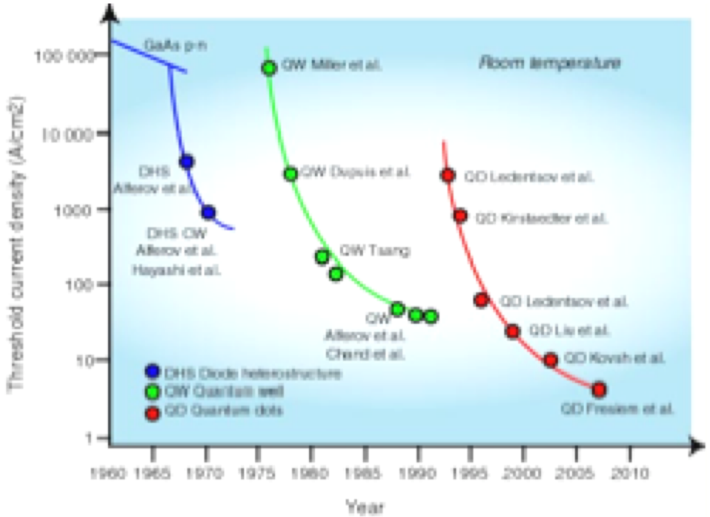


- QD lasers: unique properties that result from the **3D confinement** of charge carriers

- Higher gain, higher differential gain, lower threshold current, improved characteristic temperature and reduced α-factor

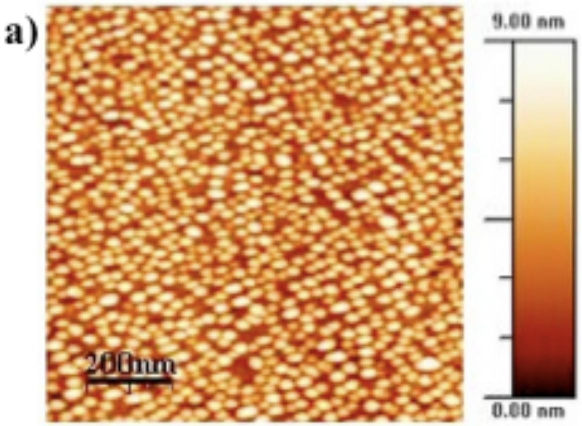
- Uncooled isolator-free operation, high speed directly modulated lasers and penalty-free data transmission on long transmission spans

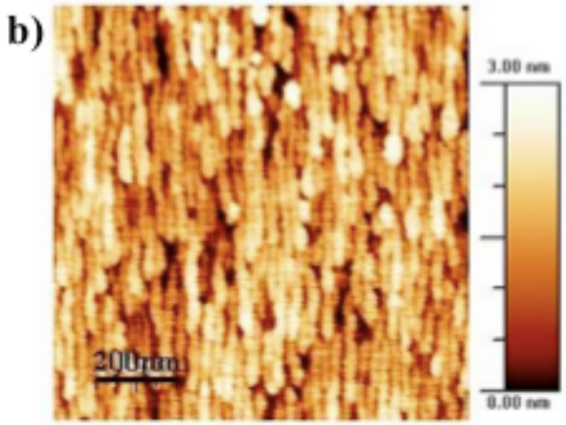
- These atomic-like nanostructures can theoretically offer **superior laser performance compared to QW based counterparts at a lower cost (low threshold current)**

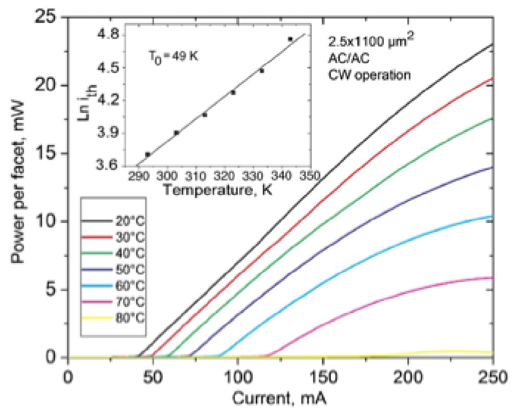


Dot vs Dash

DOTS **DASHS**







- InP-lasers based on low dimensional nanostructures and emitting@1.55µm
- InP(100) substrates, the growth of thin InAs layers leads to the formation of elongated dots, called **dashes**
- InP(311)B substrates to grow **truly three dimensional QDs**
- The most promising results, based on the optimization of **Dot-in-a-Well** (DWELL) design, reports T_0~80 K keeping a threshold as low as 10 mA

Single-Frequency

- Short-cavity lasers are the **simplest of the single-mode lasers**
- If a short FP cavity is used, **the frequency spacing between longitudinal modes gets larger**
- When the cavity length is chosen so that the mode spacing is comparable to the width of the optical gain spectrum, **only one mode is close enough to the gain peak to lase**

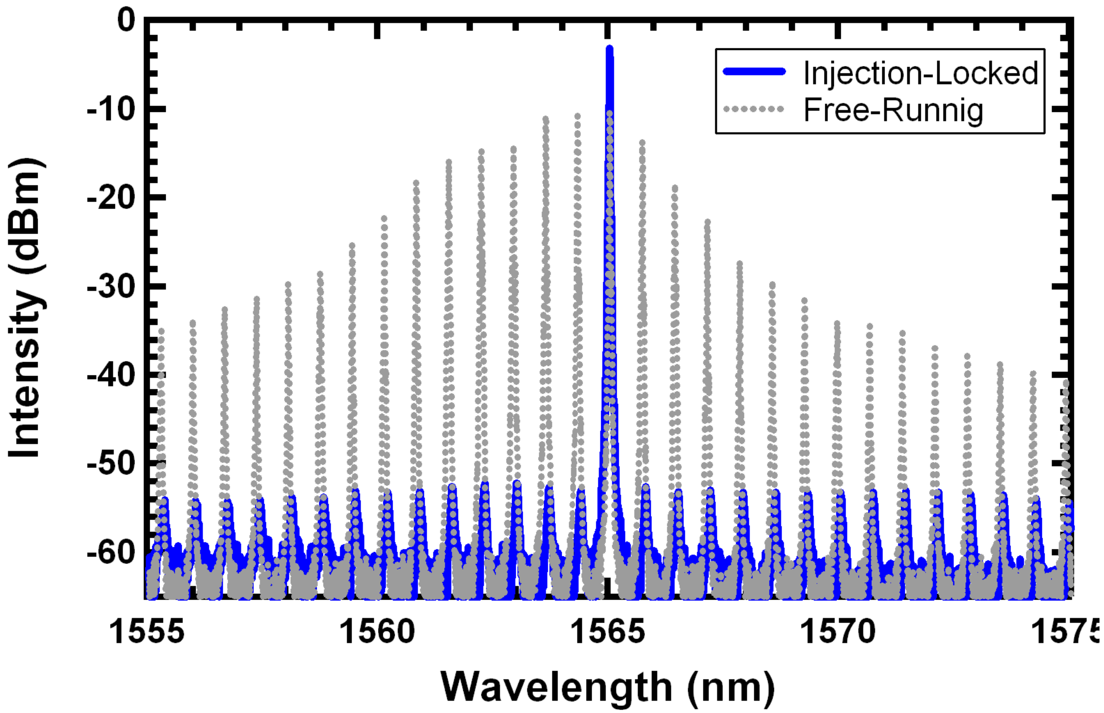
BUT

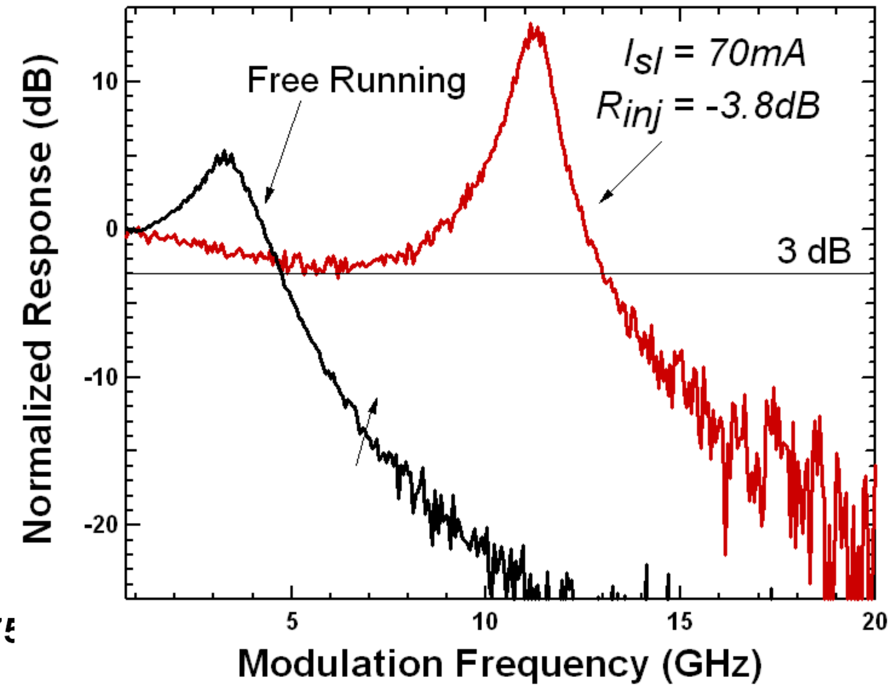
- Shortening the laser cavity **reduces the available optical gain**
- The active layer **must have a very high gain and the optical feedback must be maximized**
- Short-cavity lasers with enhanced facet reflectivities (>85%) can operate under **CW conditions in a single-mode**
- Cavity length ranges from **50 μm to 100 μm**

Single-Frequency

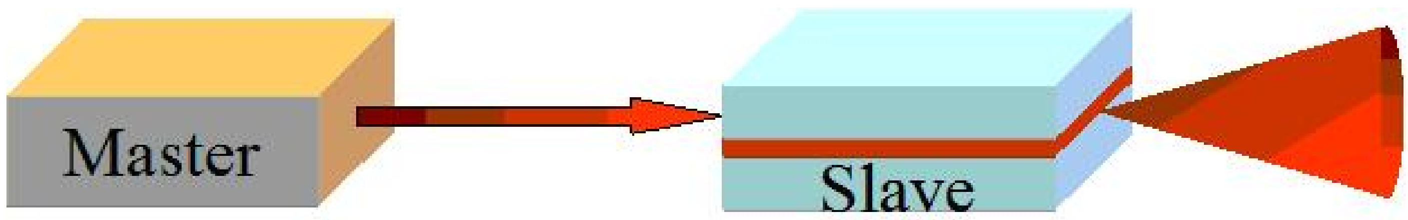
- Injection-Locked advantages over free-running lasers:
  - Increased Modulation Bandwidth
  - Reduced Linewidth and Chirp
  - Reduced Relative Intensity Noise
  - Suppression of mode hopping

$$\Delta f = f_{master} - f_{slave}$$

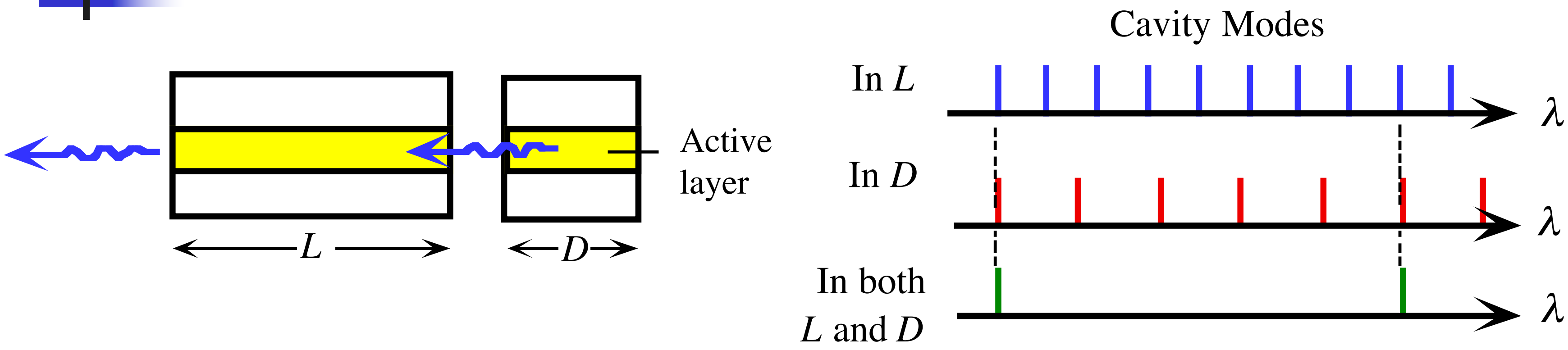




Single-Frequency

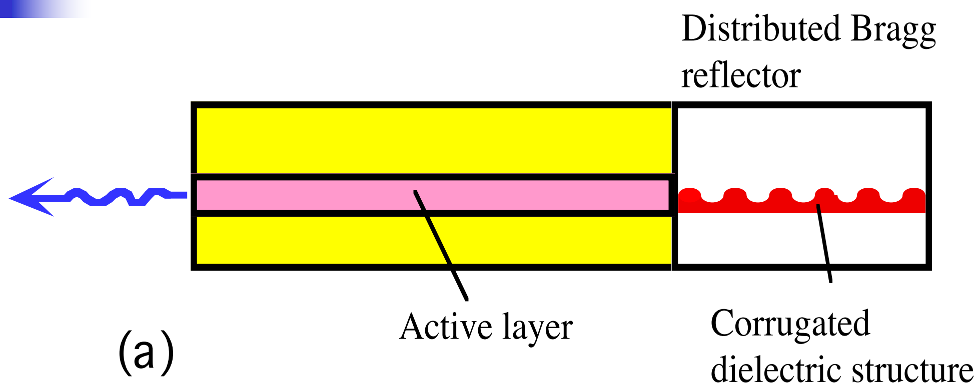


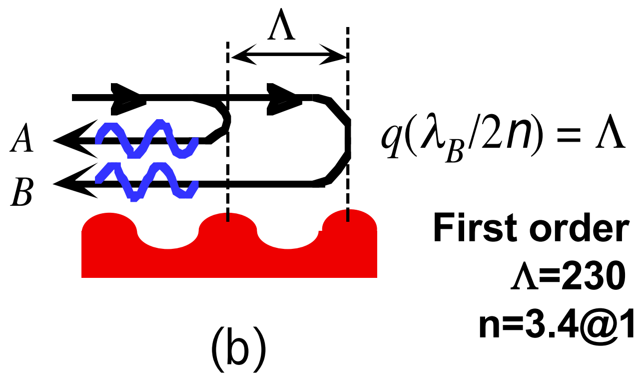
- Single-mode emission may be achieved using the **injection-locking technique**
- The injection-locking technique is based on **light injection from a master laser into the cavity of a slave laser**
- If the wavelength of the injected light is within a certain detuning range, which depends mainly on the injected power, **the frequency of the slave laser locks onto that of the master laser**



- **External-cavity lasers** consist of one FP cavity (optical gain) and an external cavity (optical feedback)
- In-phase feedback occurs for only laser modes whose lasing wavelength coincides with one of the longitudinal modes of the external cavity
- High SMSR, tunable, **poor integration, mechanical and thermal instabilities**
- **C^3 lasers**: monolithic, two FP sections driven independently The coupling element is simply an air gap which is of about 5µm wide (multiple of $\lambda/2$)
- High SMSR, reduced frequency chirp, bistability for optical logic operations or optical switching

Single-Frequency

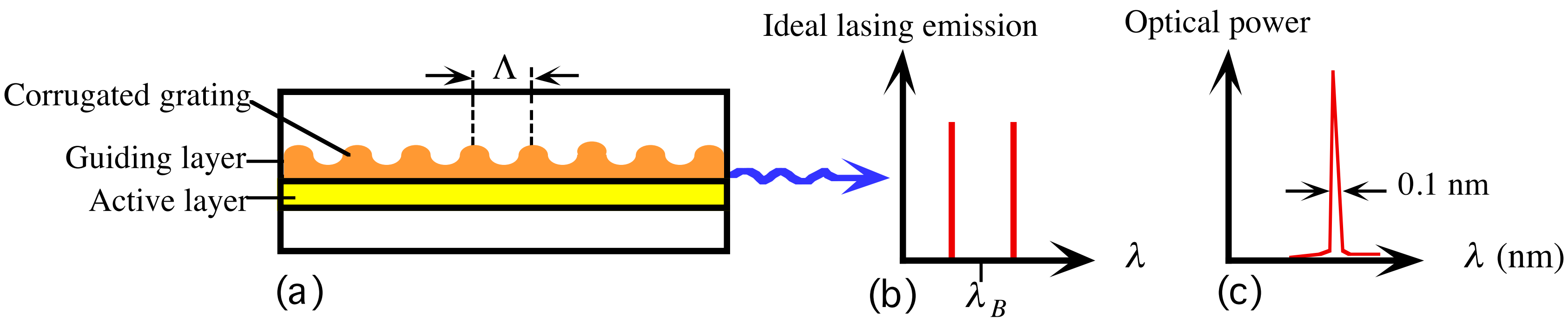




First order grating:
Λ=230 nm,
n=3.4@1.5 µm

- ❑ DBR lasers: periodic structures to provide **distributed frequency-selective feedback**
- ❑ Built-in grating ⇒ **periodic perturbation in the refractive index, and feedback occurs by Bragg diffraction**
- ❑ The longitudinal mode closest to the **Bragg wavelength** has the lowest threshold gain
- ❑ DBR lasers use **gratings etched outside the active region**
- ❑ **Optical gain and wavelength tuning** are provided by the active region and the Bragg section
- ❑ Passive phase-control section is used to ensure **single-mode operation**

Single-Frequency

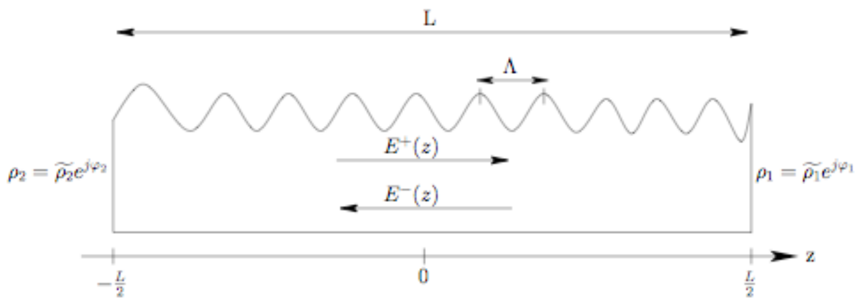


❑ The **feedback in DFB laser** is provided by the **grating** that runs along the active region

❑ Periodic perturbations in the refractive index along the laser cavity provide **frequency-selective feedback**

❑ In a DFB laser, the optical field can be written as a **superposition of counter-propagating waves**

$$E(z) = E^{+}(z)e^{-i\beta_B z} + E^{-}(z)e^{i\beta_B z}$$



Single-Frequency

- Coupled-Wave equations

$$-\frac{dE^+(z)}{dz} + (\alpha - i\delta)E^+(z) = i\kappa E^-(z)$$

$$\frac{dE^-(z)}{dz} + (\alpha - i\delta)E^-(z) = i\kappa E^+(z)$$

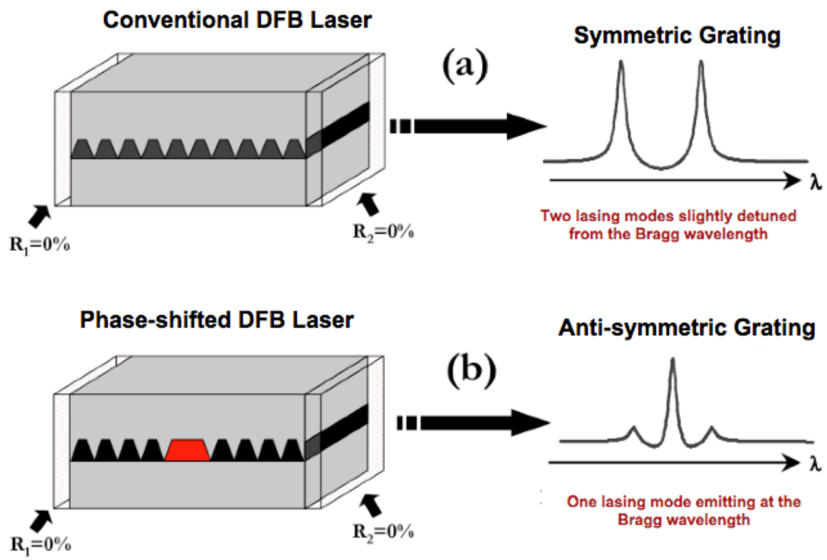
- This set of differential equations takes into account the **coupling between the counter-propagating fields through the grating coupling coefficient**
- Resolution allows to determine the **transcendental equation of a DFB laser as well as the propagation constant**
- Any finite values found for the propagation constant does correspond to a **propagating mode into the DFB laser**
- DFB lasers **suffer from wavelength chirp during high-speed modulation** because the carrier-induced variation of the refractive index causes the effective pitch of the grating to change

Single-Frequency

❑ DFB lasers with uniform gratings and cavities **do not lase at the Bragg wavelength ⇒ two-mode lasing**

❑ Single-mode emission: **phase-shifting the grating by λ/4 moves the lasing mode to the Bragg wavelength**

❑ **Increased LSHB** (higher optical intensity in the region of the phase-shift) **reduced carrier concentration at the center of the laser**



❑ DFB laser: **the optical confinement factor and the grating coupling coefficient are different for TE and TM modes**

❑ For some values of active layer thickness **both TE and TM modes may lase simultaneously**