Laser diodes

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Who am I?

- RTD-B at Electronic and Telecommunication Department, Politecnico di Torino.
- PhD (XVIII cycle) on Numerical simulation of multi-sections and multi-electrodes laser diodes.
- During the last 15 years, I worked in a group focused on the numerical analysis and simulation of
  - edge-emitting laser diodes for high bit-rate telecom applications;
  - semiconductor optical amplifiers (SOAs) and LEDs for telecom and medical applications;
  - low dimensionality structures (Quantum Dots) for innovative active materials;
  - anti- and high-reflection coating layers.

Summary

- Introduction to laser devices
- Historical notes
- Semiconductor (diode) lasers
- Active material
- Optical cavity (Edge emitting, VCSEL)
- Laser Threshold
- Small signal and large signal modulation
- Laser failure due to radiations

What is a LASER? a definition

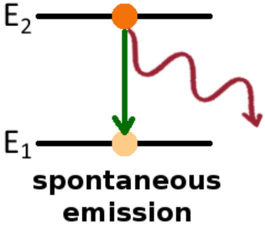
- A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation.
- A laser differs from other sources of light in that it emits light coherently.
  - Spatial coherence allows a laser to be focused to a tight spot and to stay narrow over great distances (collimation)
  - Temporal coherence allows a laser to emit light with a very narrow spectrum, i.e., it can emit a single color of light

Ingredients

- Three main ingredients are required to create a Laser:
  1. An active material, where the stimulated emission process occurs;
  2. An external (optical or electrical) injection, to trigger the stimulated emission mechanism;
  3. An optical resonator, such as a Fabry-Pérot cavity, or a ring structure: it provides the selection of the lasing modes.

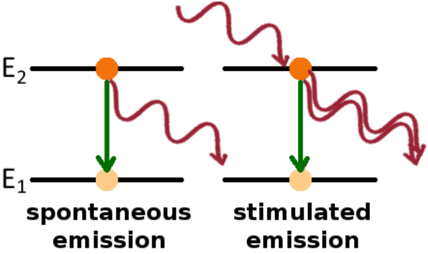
Photons spontaneous emission

- We consider a two-levels system with energies E_1 (ground or fundamental state) and E_1 (excited state).
- An electron in an excited state may spontaneously decay into a lower energy level, releasing energy in the form of a photon
  - the emitted photon has a random direction
  - Einstein coefficient A_{21} indicates the probability per unit time that an electron in state 2 will decay spontaneously to state 1, emitting a photon with an energy $E_2 - E_1 = h\nu$



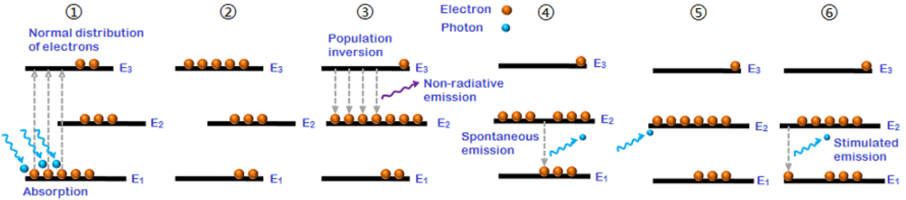
Photons stimulated emission

- Photon emission can be also stimulated by other incoming photons (stimulated/induced emission)
  - Einstein coefficient B_{21}, which gives the probability per unit time per unit spectral energy density of the radiation field that an electron in state 2 will decay to state 1, emitting a photon with an energy $E_2 - E_1 = h\nu$.
  - the emitted light wave will be coherent with the incoming wave, triggering a chain reaction.
  - stimulated emission only occurs for incoming photons that have a photon energy close to the energy of the material transition.



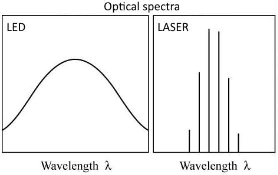
Population inversion

- Only the excited atoms can amplify light; atoms in the ground state absorb it.
- Net amplification can be obtained if more than 50% of the atoms are in the excited state population inversion.
- An external pumping mechanism is then required.
- Material amplification ("gain") is strongly frequency dependent and exhibits a maximum $\lambda_{max}(\mu m) \approx 1.24/E_{gap}(eV)$
- Gas and solid state lasers typically involve a three- of four levels system.



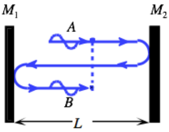
Laser cavity

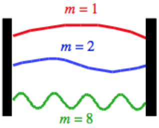
- LEDs and lasers share the same physical mechanisms of photons generation
- In the lasers the optical resonant cavity allow to limit the emission to the cavity modes (spectral coherence)
- The optical cavity is created, e.g., using terminal facets reflectivity o Bragg gratings, or using ring configurations

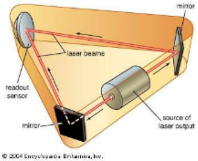


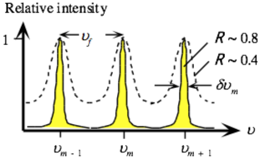
LED Versus Laser

Characteristic	LED	Laser
Output power	Lower	Higher
Spectral width	Wider	Narrower
Numerical aperture	Larger	Smaller
Speed	Slower	Faster
Cost	Less	More
Ease of operation	Easier	More difficult





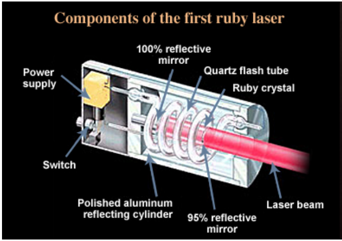


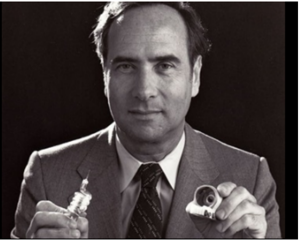


Laser history

A short history

- The first laser was built in 1960 by Theodore H. Maiman at Hughes Research Laboratories, based on theoretical work by Charles Hard Townes and Arthur Leonard Schawlow.





- It still works! https://www.youtube.com/watch?v=9wMBi3E818A

A longer history

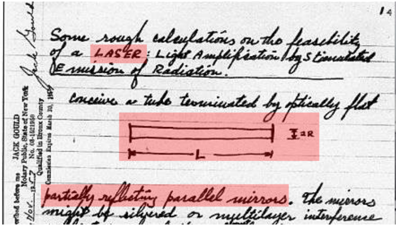
- In 1917, Albert Einstein established the theoretical foundations for the laser and the maser in the paper "On the Quantum Theory of Radiation" via a re-derivation of Max Planck's law of radiation, conceptually based upon probability coefficients (Einstein coefficients) for the absorption, spontaneous emission, and stimulated emission of electromagnetic radiation.
- In 1928, Rudolf W. Ladenburg confirmed the existence of the phenomena of stimulated emission and negative absorption.
- In 1947, Willis E. Lamb and R. C. Retherford found apparent stimulated emission in hydrogen spectra and effected the first demonstration of stimulated emission.
- In 1950, Alfred Kastler proposed the method of optical pumping, experimentally confirmed, two years later, by Brossel, Kastler, and Winter.
- In 1951, Joseph Weber submitted a paper on using stimulated emissions to make a microwave amplifier.
- In 1953, Charles H. Townes and graduate students James P. Gordon and Herbert J. Zeiger produced the first microwave amplifier, a device operating on similar principles to the laser, but amplifying microwave radiation rather than infrared or visible radiation.

A longer history

- Meanwhile, Nikolay Basov and Aleksandr Prokhorov were independently working on the quantum oscillator using more than two energy levels. These gain media could release stimulated emissions between an excited state and a lower excited state, not the ground state, facilitating the maintenance of a population inversion.
- In 1955, Basov and Prokhorov suggested optical pumping of a multi-level system as a method for obtaining the population inversion, later a main method of laser pumping.
- In 1957, Charles H. Townes and Arthur L. Schawlow, then at Bell Labs, began a serious study of the infrared laser. As ideas developed, they abandoned infrared radiation to instead concentrate upon visible light. The concept originally was called an "optical maser".
- In 1958, Bell Labs filed a patent application for their proposed optical maser.
- Moreover, in 1958, Prokhorov independently proposed using an open resonator. Elsewhere, in the U.S., Schawlow and Townes had agreed to an open-resonator laser design, apparently unaware of Prokhorov's publications and Gould's unpublished laser work.

A longer history

- Simultaneously, at Columbia University, graduate student Gordon Gould was working on a doctoral thesis about the energy levels of excited thallium. In November 1957, Gould noted his ideas for a "laser", including using an open resonator (later an essential laser-device component).
  - Pages were notarized by a public notary in a candy store, on November 13, 1957.
  - After a long court battle, Gould was finally granted a patent for "Optically pumped laser amplifiers" in October 1977. When Gould's use patent was approved in 1988, it covered most of the lasers made in the US.
- At a conference in 1959, Gordon Gould published the term LASER.



A longer history

- On May 16, 1960, Theodore H. Maiman operated the first functioning laser at Hughes Research Laboratories, Malibu, California, ahead of several research teams, including those of Townes, at Columbia University, Arthur Schawlow, at Bell Labs, and Gould, at the TRG (Technical Research Group) company.
  - Maiman's laser used a solid-state flashlamp-pumped synthetic ruby crystal at 694nm wavelength; the device only was capable of pulsed operation.
- Later that year, the Iranian physicist Ali Javan, William R. Bennett, and Donald Herriott constructed the first gas laser, using He and Ne that was capable of continuous operation in the infrared. Basov and Javan proposed the semiconductor laser diode concept.
- In 1962, Robert N. Hall demonstrated the first laser diode device, made of GaAs and emitted at 850 nm the near-infrared band of the spectrum.
- Later that year, Nick Holonyak, Jr. demonstrated the first semiconductor laser with a visible emission. This first semiconductor laser could only be used in pulsed-beam operation, and cooled to liquid nitrogen temperatures (77 K).
- In 1964 Charles H. Townes, Nikolay Basov, and Aleksandr Prokhorov shared the Nobel Prize in Physics, "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle".
- In 1970, Zhores Alferov, in the USSR, and Izuo Hayashi and Morton Panish of Bell Telephone Laboratories also independently developed room-temperature, continual-operation diode lasers, using the heterojunction structure.
- In the late 1970s, researchers from the Tokyo Institute of technology demonstrated the first VCSEL, suggested by Kenichi Iga.

Types of lasers

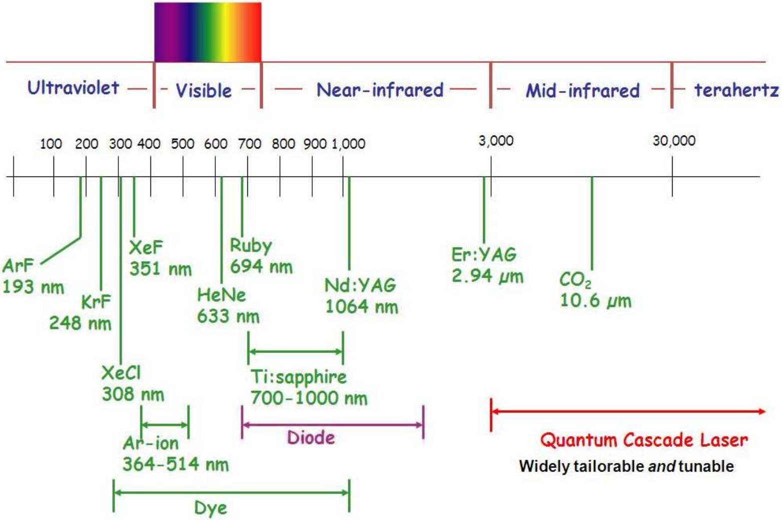
Types of lasers

- Since their discovery, lasers have been demonstrated in solid, liquid, gas and plasma materials.
- Today, the most important classes of lasers, besides the widespread diode/(or semiconductor) lasers, are gas, dye, solid-state, and fiber lasers.
- The HeNe gas laser, the widely tunable flowing-dye laser, the Nd-doped YAG (yttrium, aluminum, and garnet [a silicate mineral]) solid-state and the Er or Yb-doped silica fiber lasers are four popular examples.
- Solid-state lasers are lasers based on solid-state gain media such as crystals or glasses doped with rare earth or transition metal ions, or semiconductor lasers.
    - Although semiconductor lasers are of course also solid-state devices, they are often not included in the term solid-state lasers, the term laser diode is used instead.

Types of lasers

- A fiber laser is a laser in which the active gain medium is an optical fiber doped with rare-earth elements such as erbium, ytterbium, neodymium, dysprosium, ...
  - They are related to doped fiber amplifiers, which provide light amplification without lasing
- A HeNe laser is a type of gas laser whose gain medium consists of a mixture of helium and neon (10 to 1) inside of a small bore capillary tube, usually excited by a DC electrical discharge.
  - The best-known and most widely used HeNe laser operates at a wavelength of 632.8 nm, in the red part of the visible spectrum

Spectral coverage (in wavelength)



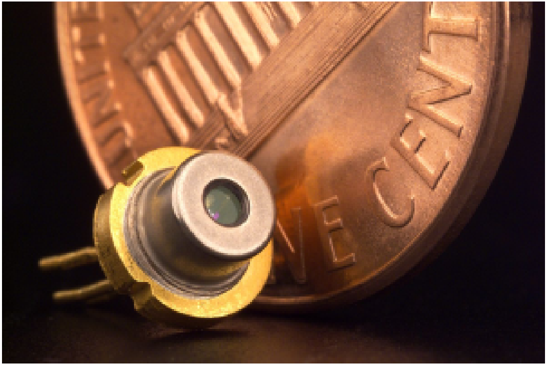
Laser diodes

Laser diodes: advantages

- Diode lasers are distinguished from these other types primarily by their ability to be pumped directly by an electrical current. They are characterized by
  - A much more efficient operation: overall power conversion efficiencies of 50% are not uncommon for a diode laser, whereas efficiencies on the order of 1% are common for gas and solid-state lasers and 10% per CO_2 gas lasers
  - High reliability or useful lifetime, has led to their widespread use in important applications such as fiber-optic communications systems. Whereas the useful life of gas or flash-lamp-pumped solid-state lasers is typically measured in thousands of hours, that of carefully qualified diode lasers is measured in hundreds of years.

Laser diodes: advantages

- Net size. Whereas gas, solid-state and fiber lasers are typically tens of centimeters in length, diode laser chips are generally about the size of a grain of salt, although the mounting and packaging hardware increases the useful component size to the order of a cubic centimeter or so.



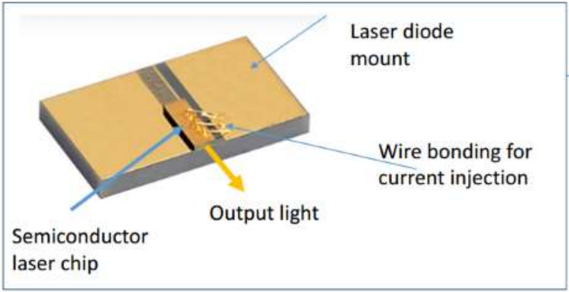
Laser diodes: advantages

- Low cost. The diode lasers are mass-produced using wafer scale semiconductor processes, which makes them really inexpensive compared to all other types of lasers.
- Easy integration. The semiconductor origins of diode lasers allows for semiconductor integration techniques to be applied, and for multiple building blocks to be defined along the common waveguide, yielding functionally complex devices and opening a new field of photonic integrated circuits.

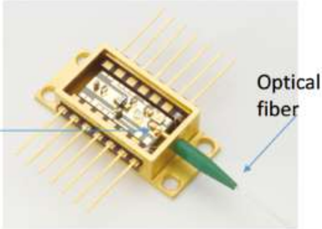
  Diode lasers with integrated optical amplifiers, modulators and similar other functions have been realized. In addition, monolithic widely tunable diode lasers and transmitters have been conceived and developed, in a footprint much smaller than that of external-cavity widely tunable lasers.

Laser diodes: examples

Laser diode chip and mounting



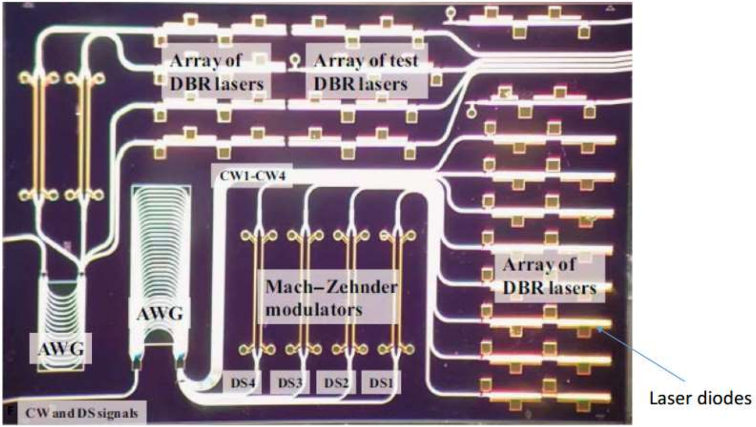
Butterfly Packaging



TO CAN packaging

https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=1832

Laser diodes: examples



Citation

K. A. Williams, E. A. J. M. Bente, D. Heiss, Y. Jiao, K. Ławniczuk, X. J. M. Leijtens, J. J. G. M. van der Tol, M. K. Smit, "InP photonic circuits using generic integration [Invited]," Photon. Res. **3**, B60-B68 (2015);
https://www.osapublishing.org/prj/abstract.cfm?uri=prj-3-5-b60

ALL integrated in one III/V semiconductor chip:

Multi-wavelength transmitter created from Bragg reflectors, optical amplifiers, phase modulators, and interferometers

Diode laser active region

- Active region: the intrinsic region of a pin junction where recombining carriers contribute to useful gain and photon emission.
- The active region is usually the lowest bandgap region within the depletion region of a pin diode for efficient injection.

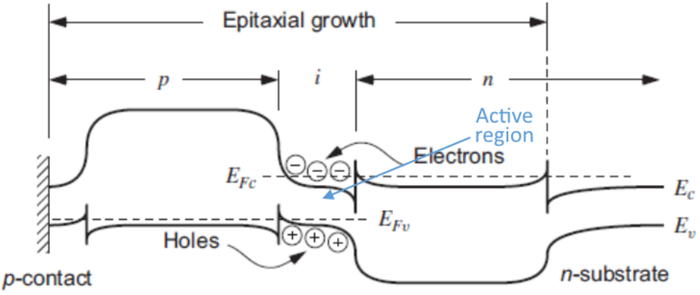
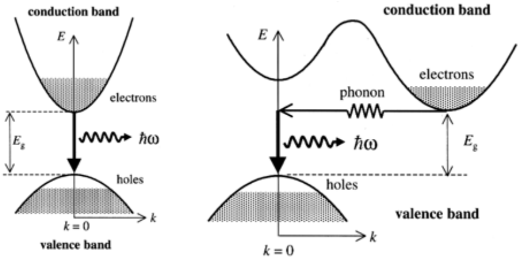


FIGURE 2.1: Band diagram of forward biased double-heterostructure diode.

Materials

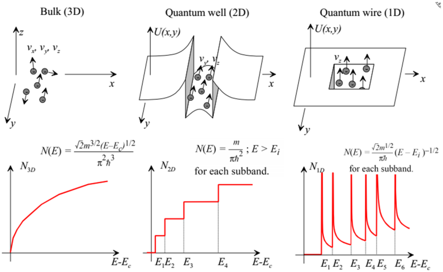
- Direct band gap semiconductor: the minimal-energy state in conduction band and the maximal-energy state in valence band are aligned (same crystal momentum): electrons can directly emit photons (many III-V compounds, such as InAs, GaAs)
- Indirect band gap semiconductor: the minimal-energy state in conduction band and the maximal-energy state in valence band are not aligned: electrons must pass trough an intermediate state (with emission of phonons) to emit photons. (Si, Ge)



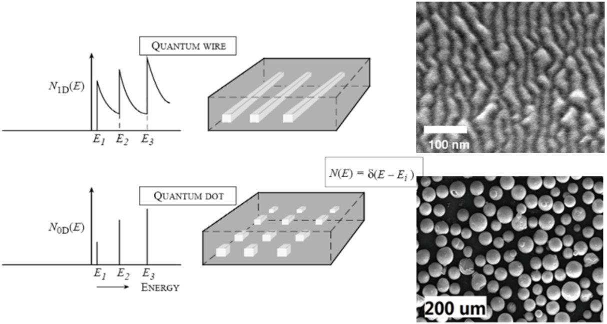
(a) direct-band-gap structure (b) indirect-band-gap structure

Reduced dimensionality structures

- Bulk materials have been replaced since the 90s by reduced dimensionality structures, e.g. Quantum Wells
- Electrons in QW have a density of states vs Energy with distinct steps; effective mass of holes is also modified
- a δ-like density of states is obtained using Quantum wire and Quantum dot materials ("artificial atoms").



Reduced dimensionality structures



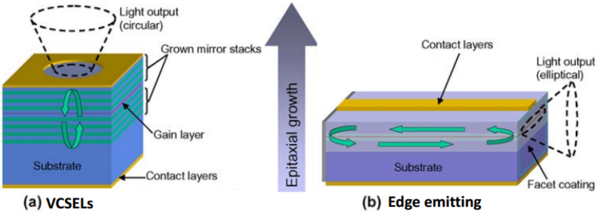
Materials

- The following is a non comprehensive list of compounds typically used in QW active materials

Laser diode material (active region / substrate)	Typical emission wavelengths	Typical application
InGaN / GaN, SiC	380, 405, 450, 470 nm	data storage
AlGaInP / GaAs	635, 650, 670 nm	laser pointers, DVD players
AlGaAs / GaAs	720–850 nm	CD players, laser printers, pumping solid-state lasers
InGaAs / GaAs	900–1100 nm	pumping EDFAs and other fiber amplifiers; high-power VECSELs
InGaAsP / InP	1000–1650 nm	optical fiber communications

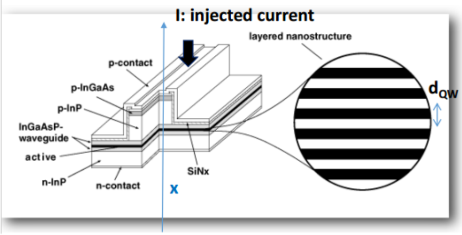
Laser cavity: comparison

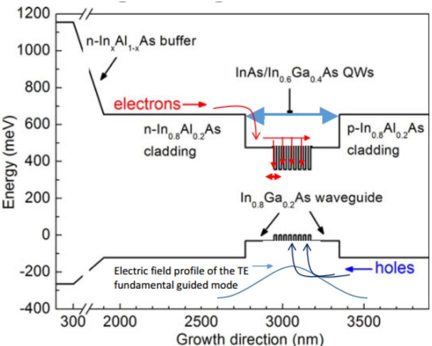
- In a vertical-cavity surface-emitting laser (VCSEL) structure, the light propagates perpendicular to the epitaxial layers and exits the top mirror stack in a circular beam.
- By contrast, in an edge-emitting structure, the light propagates along the epitaxial layers and exits through the cleaved facets in a high-diverging elliptical beam.



Laser cavity: edge emitting

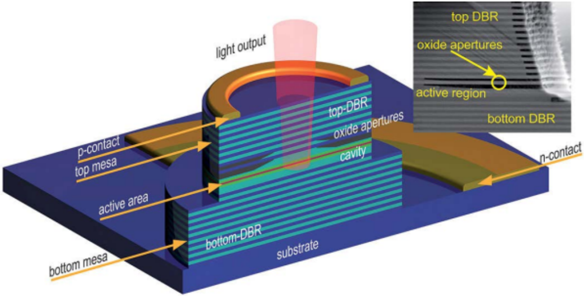
- Edge emitting (or in-plane) laser diode with ridge waveguide and Multi-Quantum-Well active region
- Carriers volume: $V = N_{QW} d_{QW} w L$ with
  - N_{QW} number of QW layers
  - d_{QW} single QW height
  - w electrode width
  - L electrode length



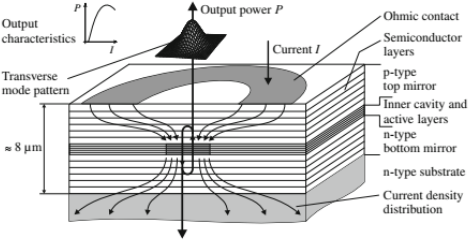


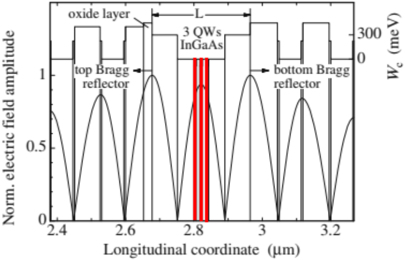
Laser cavity: VCSEL

- Vertical-cavity surface-emitting lasers (VCSELs) were introduced commercially in 1996.
- Used in many practical applications (laser mice, laser printing, precision atomic clocks, gesture recognition, solid state laser pumping, short-reach optical fiber links).
- Carriers volume: $V = N_{QW} d_{QW} \pi r^2$ with
  - N_{QW} number of QW layers
  - d_{QW} single QW heigth
  - r VCSEL radius



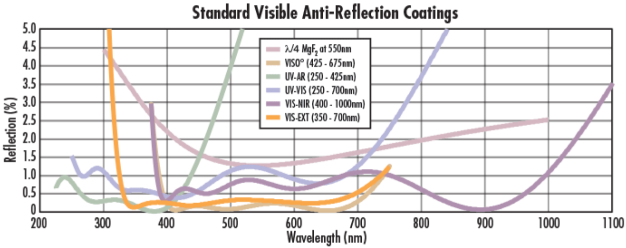
Laser structure: VCSEL





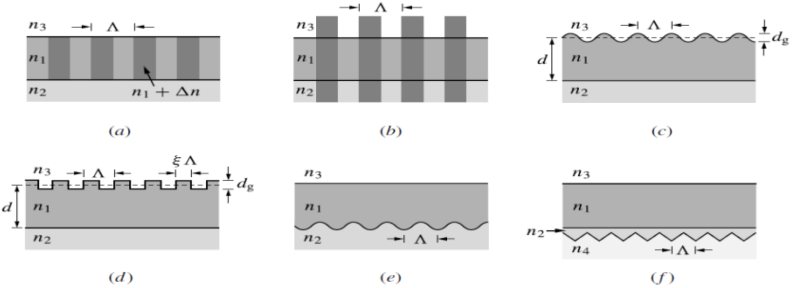
Terminal facets

- The simplest way to create an optical resonant cavity is to keep "as cleaved" the terminal facets of the edge emitting laser.
- The obtained reflection coefficient between air and semiconductor is ≈ 0.32.
- Anti- and high- reflection layers can be applied at the terminal facets to modify this value and to obtain a frequency dependent reflectivity.



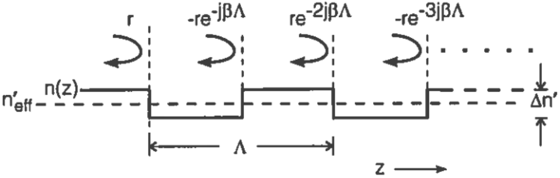
Bragg mirrors

- Wavelength dependent terminal mirrors are obtained by alternated layers of 2 different materials.
- Periodic index modulation can be permanently written in a waveguide or it can be created by an electro-optic, acousto-optic, or nonlinear optical effect.
- In VCSELs, it is simply obtained alternating layers of two different materials during the vertical growth



Grating interpretation

- Consider a square wave grating.



- The field reflection coefficient r of the high-low indices discontinuities follows the Fresnel formula $r = \Delta n_{eff}/2n_{eff}$.
- At high-low transitions, the field reflection is $-r$.
- The propagating field accumulates a phase $e^{-j\beta\Lambda/2}$ between a discontinuity and the next one.
- In order to maximize the reflection, all the terms must add up in phase at the Bragg wavelength λ_B:

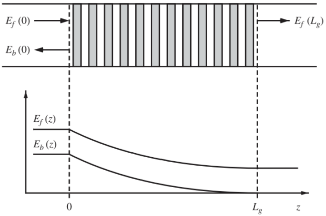
$$-re^{-j\beta\Lambda} = r \quad \rightarrow \quad \frac{2\pi n_{eff}}{\lambda_B}\Lambda = \pi \quad \rightarrow \quad \lambda_B = 2\Lambda n_{eff}.$$

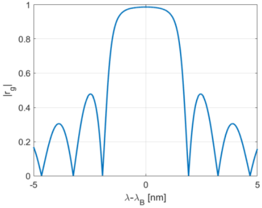
Distributed Bragg Reflector (DBR)

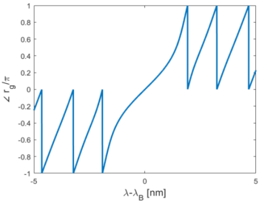
- When a DBR with length L_g is considered, the ratio between incident and exiting fields is

$$r = -\mathrm{j}\frac{\kappa \tanh \sigma L_g}{\sigma + \mathrm{j}\delta \tanh \sigma L_g}; r(\lambda_B) = -\mathrm{j}\tanh(\kappa L_g)$$

  with $\kappa = 2\Delta n/\lambda_B$ and $\sigma = \sqrt{\kappa^2 - \delta^2}$
- For small κL_g, $|r| \to \kappa L_g$, and the grating coupling coefficient κ indicates the reflectivity per unit length.







Volume of photons

- Therefore the volume V_p occupied by the electric field and by the photons is larger than to the volume V occupied by the carriers ($e^- - h^+$) that fill the wells.
- Introducing the confinement factor Γ

$$\Gamma = \frac{\int_{\text{Active}} |E(e,x,y)|^2 \mathrm{d}V}{\int_{\infty} |E(e,x,y)|^2 \mathrm{d}V}$$

  we write $V = \Gamma V_p$
- In VCSEL, the interaction between carriers and field is limited to a short region in the growth direction, leading to values of typical values of Γ much smaller than for the edge emitting case.

Laser round trip condition

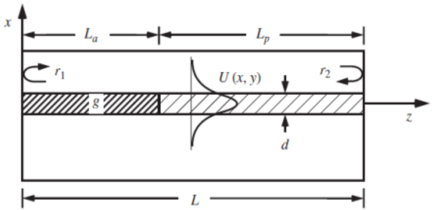
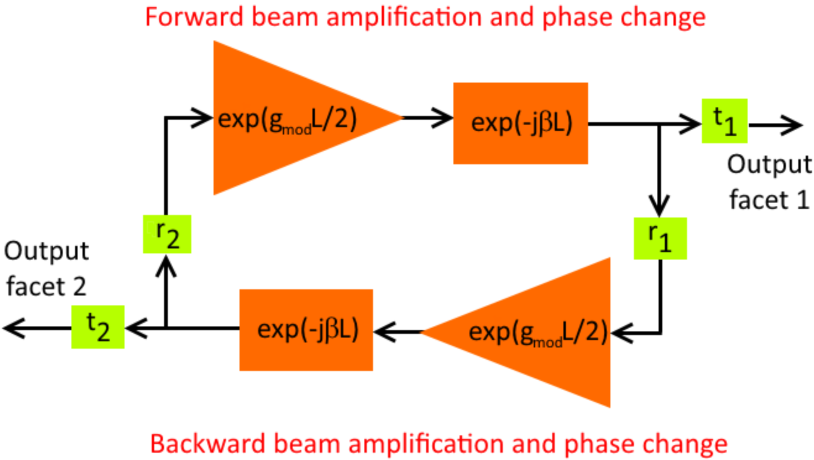


FIGURE 2.6: Generic laser cavity cross-section showing active and passive sections (no impedance discontinuity assumed) and the guided-mode profile.

- The TE field in the cavity is $E(x, y, z; t) = \hat{y} U(x, y) E_0 e^{j\omega t} e^{-j\tilde{\beta} z}$
- Starting from z^+ and moving toward left, we observe that the field
  - is first (partially) reflected at the left facet
  - then propagates toward right for distance L
  - gets (partially) reflected at the right facet
  - finally propagates toward left for distance L
- Assuming $L_p = 0$, the Round Trip RT is then

$$RT = r_1 e^{-j\tilde{\beta} L_a} r_2 e^{-j\tilde{\beta} L_a} = r_1 r_2 e^{-2j\beta L_a} e^{\frac{\Gamma g - <\alpha_i>}{2} L_a} \quad (1)$$

Laser and oscillator model



Laser round trip condition

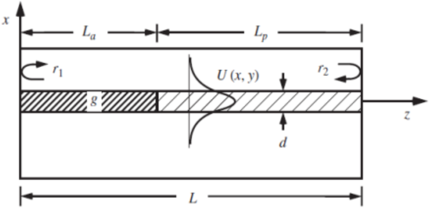


FIGURE 2.6: Generic laser cavity cross-section showing active and passive sections (no impedance discontinuity assumed) and the guided-mode profile.

- To sustain steady-state oscillation (Barkhausen stability criterion): $RT = 1$
  - Modulus (gain) condition: $|RT| = 1$
  - Phase condition: $\angle RT = 2m_l\pi$, $m_l \in \mathcal{Z}$
- For the other, non-lasing, longitudinal cavity modes:
  - Modulus (gain) condition: $|RT| < 1$
  - Phase condition: $\angle RT = 2m\pi$, $m \in \mathcal{Z} \neq m_l$

Phase condition

- From the phase condition $\angle RT = 2m\pi$, $m \in \mathcal{Z}$ we get $2\beta_r L_a = 2m\pi$ But since $\beta_r = \frac{2\pi}{\lambda} n_{eff}$ we finally obtain that the longitudinal mode associated to index m is placed at

$$\lambda_m = 2 n_{eff} L_a / m \tag{2}$$

- More precisely, in a dispersive medium, we use the Taylor expansion of the real part of the propagation constant around the wavelength λ_0 at which the effective refractive index n_{eff} as Been measured:

$$\beta_r(\omega) = \beta_r(\omega_0) + \frac{\partial \beta_r}{\partial \omega}(\omega - \omega_0) + \mathcal{O}(\omega^2)$$

Observing that $\frac{\partial \beta_r}{\partial \omega} = \frac{1}{v_g}$ and $\omega = 2\pi c/\lambda$, we get

$$\lambda_m = \frac{2 n_g}{\frac{m}{L_a} - \frac{2}{\lambda_0}(n_{eff} - n_g)} \tag{3}$$

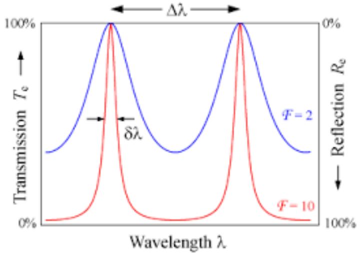
with $n_g = c/v_g$ group refractive index.
As a first approximation, $\lambda_m = 2 n_g L_a / m$

Free spectral range

- The free spectral range (FSR) is the separation between two longitudinal modes m and $m+1$, in wavelength or frequency

$$|d\lambda| = |\lambda_{m+1} - \lambda_m| = |\frac{2n_g L_a}{m+1} - \frac{2n_g L_a}{m}| \approx \frac{2n_g L_a}{m^2} \quad \text{if } m \gg 1 \qquad (4)$$

- Since $|df| \approx \frac{c}{\lambda_m^2}|d\lambda|$, we have
  At 1300nm 1nm $\rightarrow$ 178 GHz; 1GHz $\rightarrow$ 5.6pm
  At 1500nm 1nm $\rightarrow$ 125 GHz; 1GHz $\rightarrow$ 8.0pm



Gain condition

- For the lasing mode, at threshold we have $|RT| = 1$; from Eq.(1) it follows

$$r_1 r_2 e^{\frac{\Gamma g - <\alpha_i>}{2} L_a} = 1$$

- The threshold gain Γg_{th} is then

$$\Gamma g_{th} = \frac{2}{L_a} \log \frac{1}{r_1 r_2} + < \alpha_i >$$

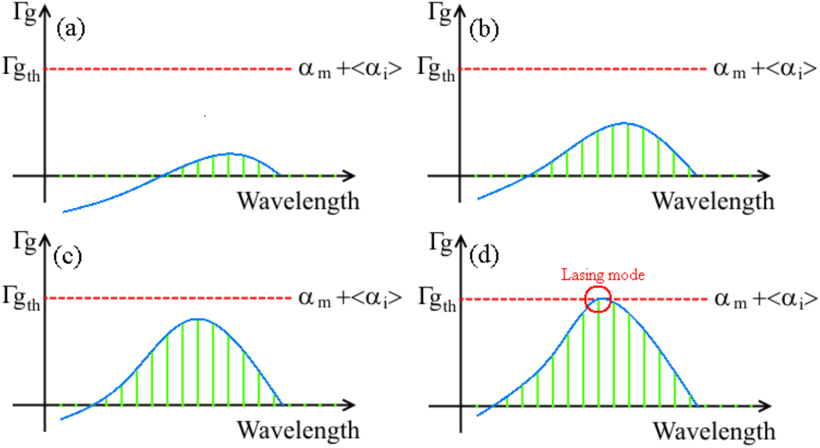
- We define the "power" mirror losses α_m as $2 \log(1/r_1 r_2)/L_a = \log(1/R_1 R_2)/L_a$ (N.B.: for cleaved facets $r_1 = r_2 = \sqrt{(}0.32)$, $\alpha_m \approx 2/L_a$)
- Threshold: the modal gain equals all the cavity losses (mirror+material)

$$\Gamma g_{th} = \alpha_m + < \alpha_i > \tag{5}$$

Laser threshold

- Among the several cavity longitudinal modes, there is only one or just few modes that satisfies the laser threshold condition $RT = 1$.
- When the laser threshold is reached, the gain does not increase with current anymore: the gain is clamped at threshold.
- Below threshold: a current increase results in an increase of carriers and gain.
- At threshold: gain=losses for at least one cavity mode.
- Above threshold: the gain is clamped; a current increase results in an increase of the emitted photons

Laser threshold



$$I_a < I_b < I_c < I_d = I_{th}$$

Laser rate equations: carriers

- The temporal evolution of the carriers density N in the active region depends on the generation rate G_{gen} and the recombination rate R_{rec}:

$$\frac{dN}{dt} = G_{gen} - R_{rec} \tag{6}$$

- The generation term depends on the injected current density I/V and the injection efficiency η_i (fraction of injected carrier that ends in the active region)

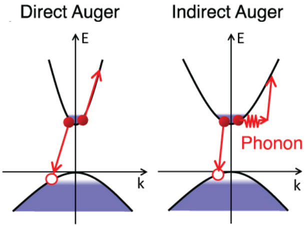
$$G_{gen} = \frac{\eta_i I}{qV} \tag{7}$$

- The recombination term includes different effects, related to the non-radiative (R_{nr}), radiative (R_{sp}), Auger (R_{Au}) recombinations and to stimulated emission of photons (R_{st}):

$$R_{rec} = R_{sp} + R_{nr} + R_{st} = BN^2 + AN + CN^3 + R_{st} \tag{8}$$

Recombination rates

- AN addresses, e.g., impurity recombinations (Shockley-Read-Hall recombination: an electron in transition between bands passes through an energy state (localized state) created in the band gap by material impurities).
- BN^2 accounts for the spontaneous emissions of incoherent photons, over the whole emission bandwidth
- CN^3 is related to Auger processes, i.e. non radiative recombination between $e^- - h^+$ imparting their transition energy to another e^- (direct Auger) or to another e^- and a phonon (indirect Auger)



Carrier lifetime

- If we inject a certain amount of carrier in the active region and we stop the injection, the accumulated carrier density will decay with an exponential rate

$$\frac{dN}{dt} = -\frac{N}{\tau}$$

with τ carrier lifetime in the order of nanoseconds

Gain model

Calculated gain spectra from concepts of lesson B3

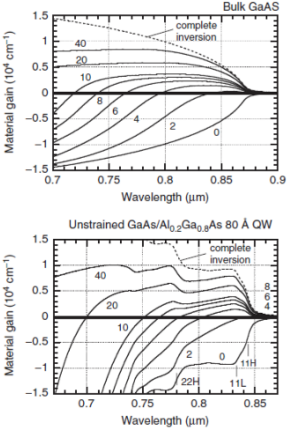


FIGURE 4.24: TE gain spectrum versus carrier density in GaAs based materials. Indicated values are the sheet carrier densities: $\times 10^{12}$ cm^{-2} (the bulk "sheet" density assumes an 80 Å width).

Plot of the gain versus carrier density

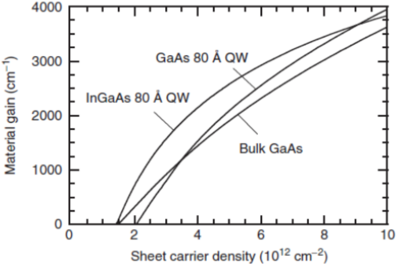


FIGURE 4.26: Peak TE gain versus sheet carrier density in GaAs

Gain model

- The gain versus carrier density shown in the previous slide can be approximated by a simple three-parameters logarithmic formula:

$$g(N) = G_0' \log \frac{N + N_s}{N_{tr} + N_s} \tag{9}$$

  with

  - G_0' empirical gain coefficient used for the fitting
  - N_{tr} is transparency carrier density, i.e. $g(N_{tr}) = 0$
  - N_s is a shift to force the natural logarithm to be finite at $N = 0$ such that the gain equals the unpumped absorption due to the band-to-band transitions

- The expression above is often approximated as:

$$g(N) = G_0 \log \frac{N}{N_{tr}} \tag{10}$$

Laser threshold

- At threshold ($I = I_{th}$), $R_{st} = 0$ and $\Gamma g_{th} = \Gamma g(N_{th}) = \frac{1}{L_a} \log \frac{1}{r_1 r_2} + < \alpha_i >$
- In steady state condition Eq. (6) becomes

$$\frac{\eta_i I_{th}}{qV} = AN_{th} + BN_{th}^2 + CN_{th}^3$$

- We can then write

$$g(N_{th}) = G_0 \log \frac{N_{th}}{N_{tr}} = \frac{< \alpha_i > + \alpha_m}{\Gamma} \tag{11}$$

- and the threshold carrier density is then

$$N_{th} = N_{tr} e^{\frac{<\alpha_i> + \alpha_m}{\Gamma G_0}}$$

- The threshold current is finally

$$I_{th} = \frac{qV}{\eta_i} \left(AN_{th} + BN_{th}^2 + CN_{th}^3 \right) \tag{12}$$

Gain and carrier density vs. current

- N increases for $I < I_{th}$; it is clamped for $I > I_{th}$
- Gain clamps at the I_{th}: any increase of I above I_{th} turns into emitted photons but no carrier increase

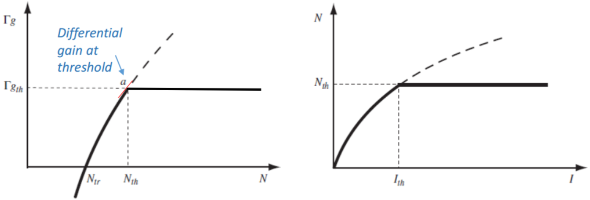


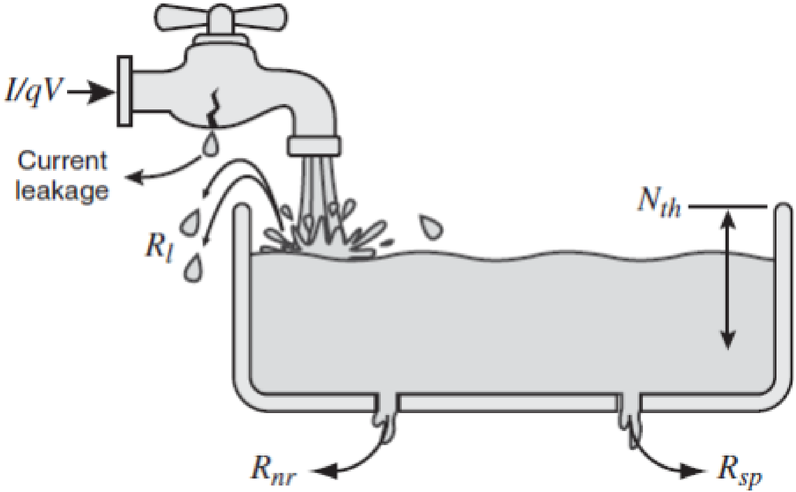
FIGURE 2.8: Gain versus carrier density and carrier density versus input current. The carrier density clamps at threshold causing the gain to clamp also.

- We define the differential gain a as the derivative of the gain respect to the carrier density

$$\frac{\partial g}{\partial N} \equiv a = \frac{G_0}{N}$$

- Linearized gain at threshold: $g = a(N - N_{th})$

Carrier equivalent model



Stimulated emission

- We can write the total number of photons generated stimulated emission per unit time as

$$R_{tot,st} = v_g \Gamma g N_{p,tot} = v_g \Gamma g N_p V_p$$

- The rate of carrier loss per unit volume V is therefore

$$R_{st} = v_g \Gamma g N_p V_p / V = v_g g N_p$$

Laser rate equations: photons

- The temporal evolution of the photon density N_p at the lasing wavelength can be written as

$$\frac{dN_p}{dt} = \Gamma v_g g N_p + \Gamma \beta_{sp} R_{sp} - \frac{N_p}{\tau_p} \tag{13}$$

with

- β_{sp} spontaneous emission coefficient, which indicates the probability for a photon generated by spontaneous emission to have the same wavelength as the lasing mode and a direction compatible with the field propagation in the cavity, therefore contributing to N_p
- τ_p the photon lifetime

Empirical gain model (with photons)

- Gain at the lasing wavelength decreases with the increase of photons
- We introduce in Eq. (9) a term to describe the gain reduction (compression) due to N_p

$$g(N, N_p) = \frac{G_0}{1 + \varepsilon N_p} \log \frac{N}{N_{tr}} \tag{14}$$

with ε gain compression factor

- We define the gain derivatives

$$a \equiv \frac{\partial g}{\partial N} = \frac{a_0}{1 + \varepsilon N_p} \tag{15}$$

and

$$a_p = \frac{\varepsilon g}{1 + \varepsilon N_p} \tag{16}$$

Photon density in steady state

- Below threshold: R_{st} can be neglected

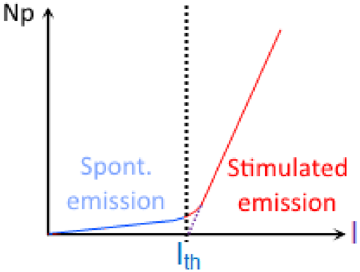
$$\beta_{sp}\Gamma R_{sp} - N_p/\tau_p = 0$$

and we obtain $N_p = \tau_p\beta_{sp}\Gamma R_{sp} = \tau_p\beta_{sp}\Gamma BN^2$

- Above threshold: N is clamped

$$\frac{\eta_i I}{qV} - AN_{th} - BNth^2 - CN_{th}^3 - v_g g_{th} N_p = 0$$

But $AN_{th} + BNth^2 + CN_{th}^3 = \eta_i I_{th}/qV$, therefore $N_p = \frac{\eta_i(I-I_{th})}{qVv_g g_{th}}$



P-I (L-I) curve

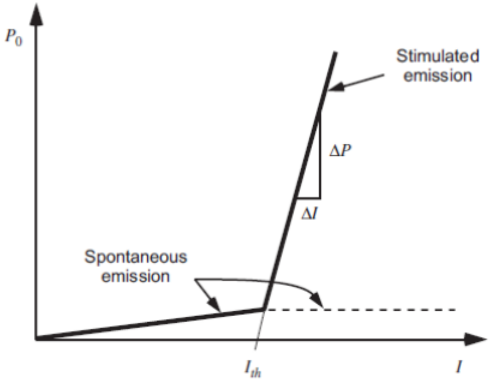


FIGURE 2.9: Illustration of output power versus current for a diode laser. Below threshold only spontaneous emission is important; above threshold the stimulated emission power increases while the spontaneous emission is clamped at its threshold value.

Optical energy and power

- The total optical energy stored in the cavity is

$$E_{OS} = \hbar\omega N_p V_p$$

- The optical output power from the two facets is

$$P_0 = \frac{1}{\tau_m} E_{OS} = v_g \alpha_m \hbar\omega N_p V_p = v_g \alpha_m \hbar\omega \frac{\eta_i (I - I_{th})}{q v_g g_{th} V} V_p$$

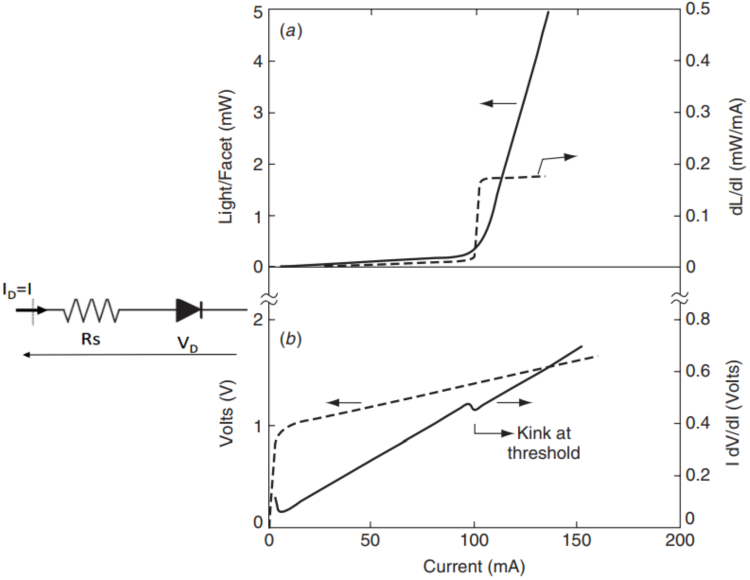
which can be finally written as

$$P_0 = \eta_i \frac{\alpha_m}{\alpha_m + < \alpha_i >} \frac{\hbar\omega}{q} (I - I_{th}) = \eta_d \frac{\hbar\omega}{q} (I - I_{th})$$

where η_d is the differential quantum efficiency.

- The PI curve slope above threshold is $\eta_d \hbar\omega / q$

VI curve



I_D=I
Rs
V_D
(a)
Light/Facet (mW)
dL/dI (mW/mA)
(b)
Volts (V)
I dV/dI (Volts)
Kink at threshold
Current (mA)
0
50
100
150
200

Summary of laser rate equations

- Rate equations for carrier and photon densities:

$$\frac{dN}{dt} = \frac{\eta_i I}{qV} - \frac{N}{\tau} - v_g g N_p$$

$$\frac{dN_p}{dt} = \Gamma v_g g N_p + \Gamma \beta_{sp} R_{sp} - \frac{N_p}{\tau_p}$$

- Explicitating τ, τ_p and R_{sp}:

$$\frac{dN}{dt} = \frac{\eta_i I}{qV} - \left(AN + BN^2 + CN^3\right) - v_g g N_p$$

$$\frac{dN_p}{dt} = \Gamma v_g g N_p + \Gamma \beta_{sp} B N^2 - v_g N_p \left(< \alpha_i > + \alpha_m\right)$$

Summary of laser rate equations

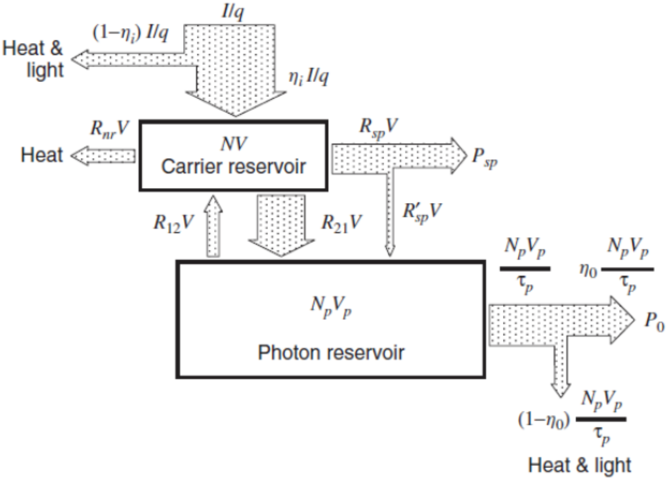
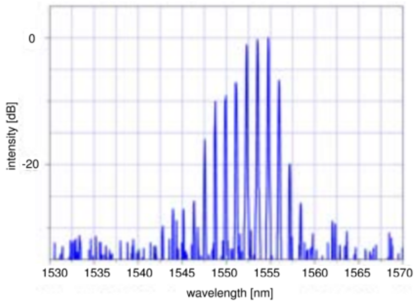
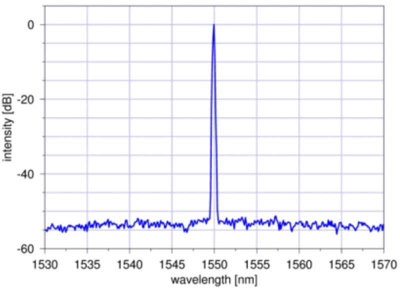


FIGURE 5.1: Model used in the rate equation analysis of semiconductor lasers.

Optical spectrum

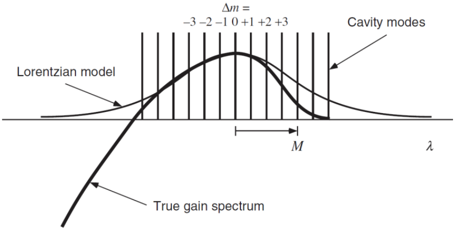
- In Fabry-Perot (FP) laser diodes several cavity longitudinal modes can reach the lasing threshold
- We have several lasing lines (left), therefore the laser emission is not one single wavelength
- Different cavity layouts are required to ensure that the laser is single mode (right): DBR and DFB lasers

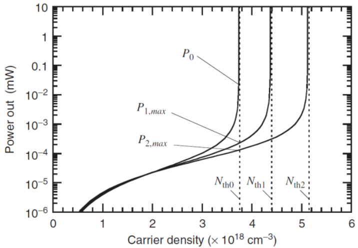




Multi-mode characteristics of FP lasers

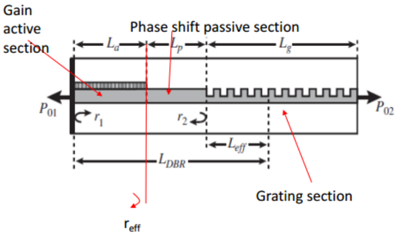
- FP lasers can exhibit multiple longitudinal mode characteristics, in particular if the cavity FSR is small if compared to the gain dispersion and various modes can reach threshold for similar levels of carrier densities.
- Moreover, the gain maximum depends on the carrier density and it's not easy to control which mode start lasing first.

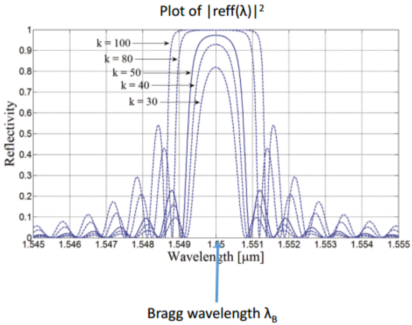




DBR laser

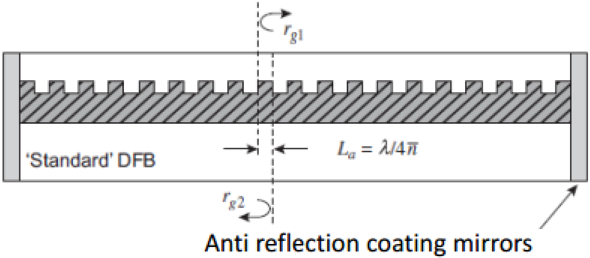
- Distributed Bragg Reflectors laser: one facet is replaced by a suitable designed Bragg Grating
- Mirror losses are now wavelength dependent since $R_2 = R(\lambda)$
- A phase shift section can be introduced to fine tune the position of the lasing mode





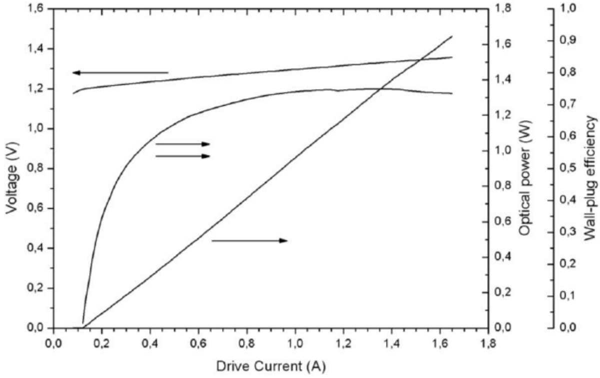
DFB laser

- Distributed Feedback laser: the grating is integrated in the active waveguide
- With the notation used in the Figure, the lasing mode wavelength and the threshold gain are obtained from the condition $r_{g_1}(\tilde{\beta}_{th})r_{g_2}(\tilde{\beta}_{th}) = -1$



Wall plug efficiency

- The input electrical power P_{in} is $I^2 R_S + IV_d$, with V_d diode voltage which is clamped at threshold
- The wall plug efficiency, defined as the ratio between optical (output) power P_O and input (electrical) power is $WPE = P_O/(I^2 R_S + IV_d)$



Temperature effects and laser heating

- The dissipated power $P_d = P_{in} - P_0$ turns into heat and causes an increase of the device temperature $\Delta T \propto P_d$
- This in turn causes a decrease of the gain ($\leftarrow$ reduction of P) and a variation of the refractive index ($\leftarrow$ shift in wavelength)

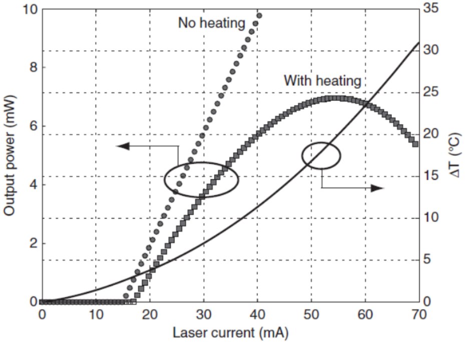
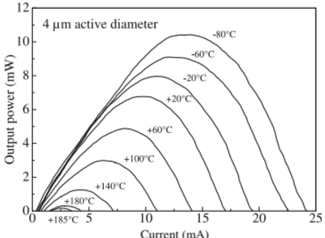


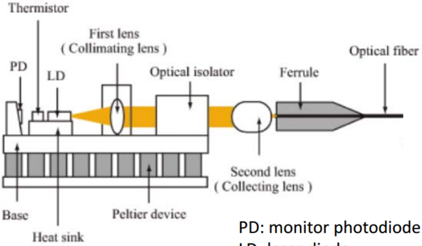
FIGURE 2.17: laser heating as a function of bias current, L-I curve with thermal roll off (temperature effects taken into account) and ideal L-I curve (for no heating) are shown.

Temperature effects in VCSELs

- As in DFB and DBR, the emission wavelength of a VCSEL is determined by the cavity resonance and not by the gain peak
- For VCSELs in the 900 nm range, mode shift is ≈ 0.07 nm/K
- The QWs peak shift (due to bandgap shrinkage) is ≈ 0.32 nm/K: a mutual shift of lasing mode and gain spectrum occurs.
- As a result, $I_{th}(T) = I_{th,min}(1 + C_T(T - T_{min})^2)$ with $C_T > 0$.
- With increasing driving current above threshold or increasing ambient temperature, a significant rollover of the output power characteristics is observed.

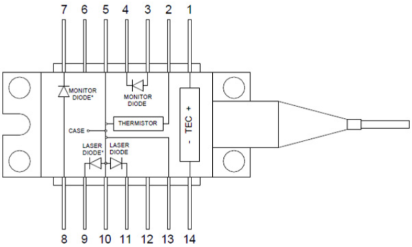


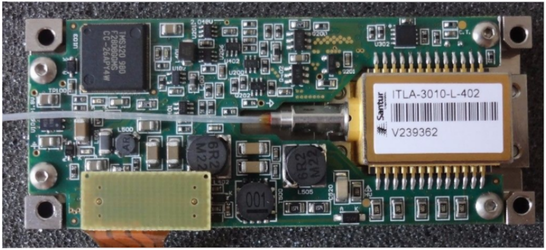
Laser packaged with temp. control



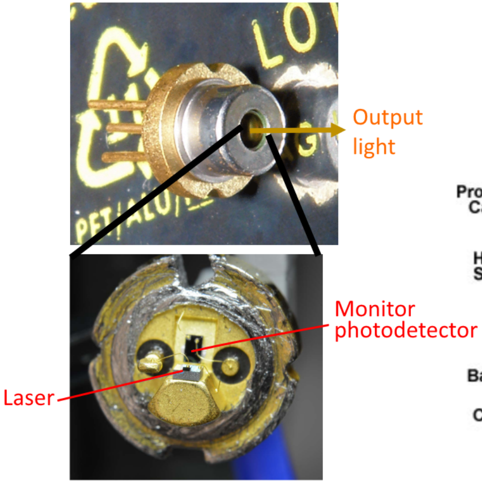
PD: monitor photodiode
LD: laser diode

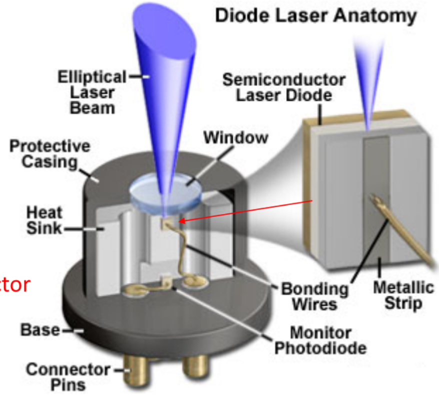
Butterfly package: example output leads



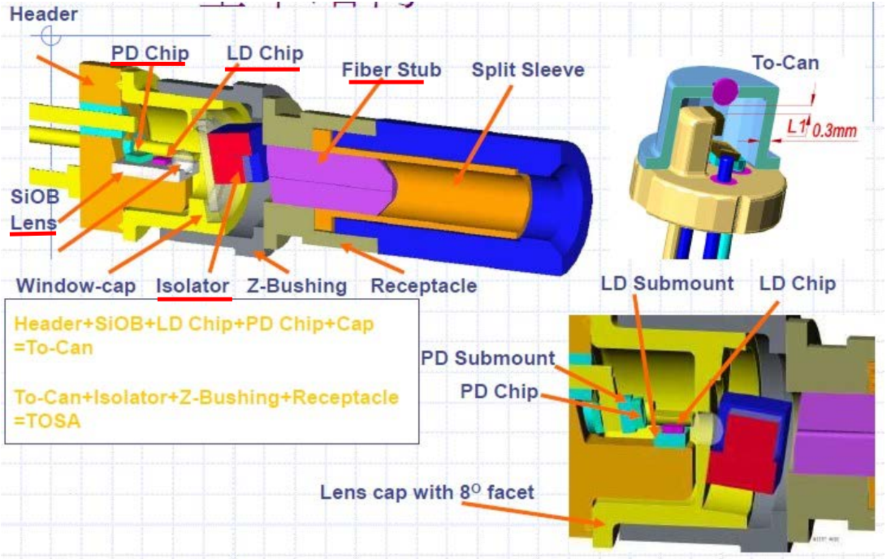


Package w/out temp. control
TO-CAN



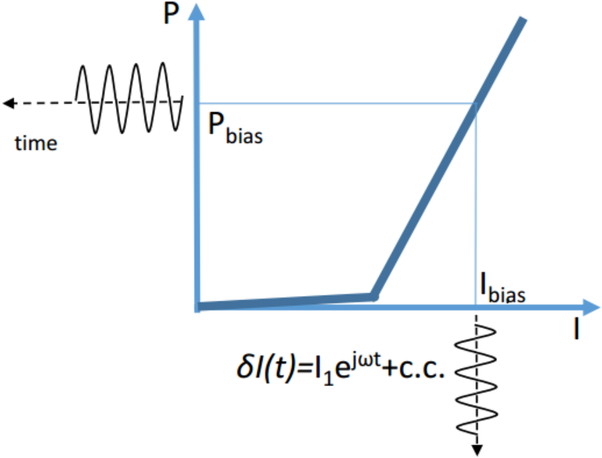


TO-CAN with fiber connector



Small and large signal Behavior

Small signal behavior



Modulation transfer function

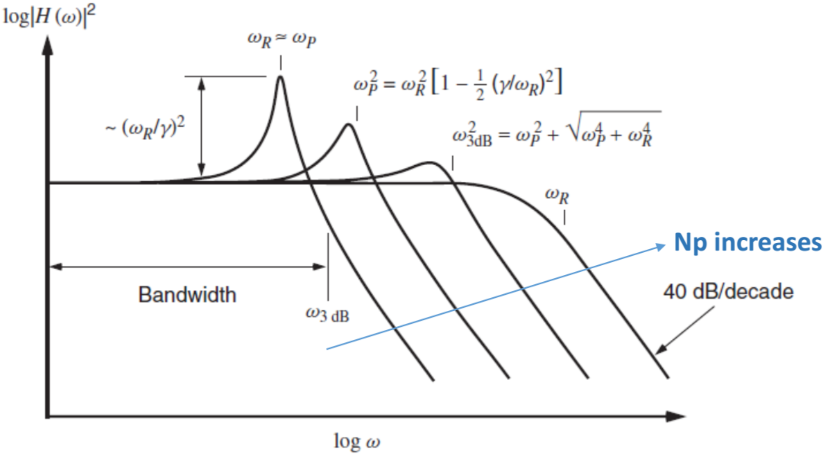


FIGURE 5.4: Sketch of the modulation transfer function for increasing values of relaxation resonance frequency and damping factor, including relationships between the peak frequency, ω_P, the resonance frequency, ω_R, and the 3 dB down cutoff frequency, ω_{3dB}.

Damping, resonance and -3dB freq.

$$\omega_R^2 \approx \frac{v_g a N_p}{\tau_p}; \quad \gamma \approx v_g a N_p \left[1 + \frac{\Gamma a_p}{a}\right] + \frac{1}{\tau_{\Delta N}}$$

- The relaxation frequency ω_R increases with photon density: moving to higher bias current the bandwidth increases. The higher is the differential gain a_0, the better it is for large modulation bandwidth.
  - MQW lasers are preferred respect to bulk lasers because they have higher differential gain and therefore large modulation bandwidth. Ideally Quantum Dot lasers should have the maximum modulation bandwidth.
- The term a contains the compression factor ε. Hence the increase of N_p causes a reduction of a and therefore a reduction of the resonance frequency ω_R
- The damping γ increases with N_p as well. The damping is also affected by the compression of the gain due to a_p and by the differential carrier lifetime $\tau_{\Delta N}$

Maximum -3dB modulation bandwidth

- The -3dB bandwidth is given by $\omega_{3dB}^2 = \omega_p^2 + \sqrt{\omega_p^4 + \omega_R^4}$
- It is maximum with respect to N_p when $\omega_p^2 = 0$, i.e., $\omega_{3dB} = \omega_R$. This condition also corresponds to the flattest modulation response.
- Since $\omega_p^2 = \omega_R^2 \left[1 - \frac{\gamma^2}{2\omega_R^2}\right]$, imposing $\omega_p^2 = 0$ we get $\gamma = \sqrt{2}\omega_R$
- the value of N_p leading to the maximum -3dB modulation freq. $f_{-3dB_{max}}$:

$$N_{p,-3dB_{max}} = \frac{2}{v_g a \tau_p} \left[1 + \frac{\Gamma a_p}{a}\right]^{-2}$$

resulting in

$$f_{-3dB_{max}} = \frac{\sqrt{2}}{2\pi\tau_p} \left[1 + \frac{\Gamma a_p}{a}\right]^{-1} = \frac{\sqrt{2}}{2\pi\tau_p} \left[1 + \frac{\Gamma \varepsilon}{a_0}\right]^{-1} =$$

$$= f_{-3dB_{max}}\big|_{\varepsilon=0} \left[1 + \frac{\Gamma \varepsilon}{a_0}\right]^{-1}$$

K factor

- It is defined as the proportionality term between damping factor γ and resonance frequency ω_R
- We observe that

$$\gamma = K f_R^2 + \gamma_0$$

with

$$K = 2\pi^2 \tau_p \left[1 + \frac{\Gamma a_p}{a}\right]$$

and

$$\gamma_0 = \frac{1}{\tau_{\Delta N}}$$

- The maximum modulation bandwidth is

$$f_{-3dB_{max}} = \sqrt{2}\frac{2\pi}{K}$$

- The K factor therefore defines the intrinsic modulation bandwidth capabilities of the laser

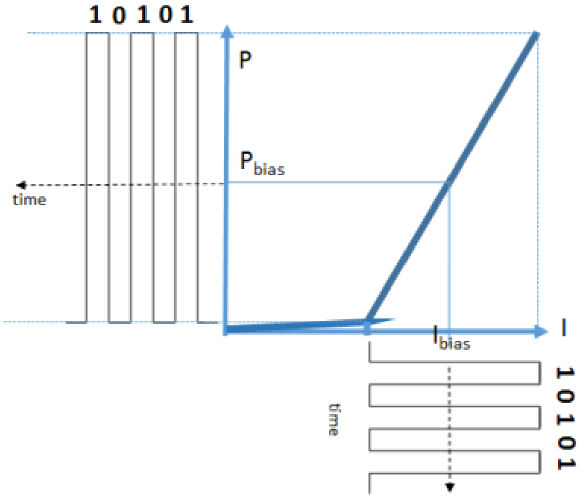
Linewidth enhancement factor

- Changes in n_{eff} causes a shift in the emission wavelength, proportional to the linewidth enhancement factor α_H (typically ranging between 2 and 6):

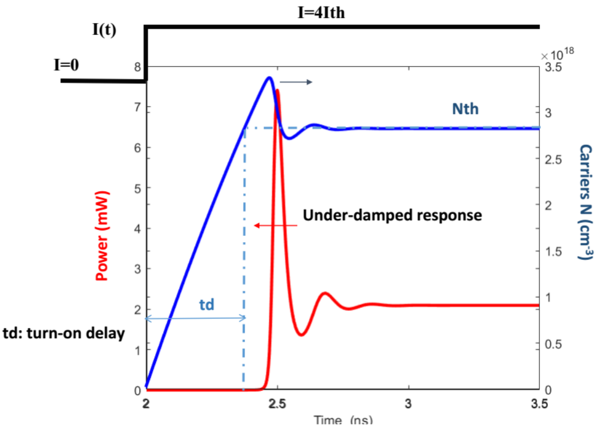
$$\alpha_H = -\frac{4\pi}{\lambda}\frac{\partial n/\partial N}{\partial g/\partial N}$$

$$\delta\nu = \alpha_H \frac{v_g}{4\pi}\frac{\partial g}{\partial N}\delta N = \frac{\alpha_H}{4\pi} v_g a \delta N$$

Large signal response



Response to a current step



Response to a current step

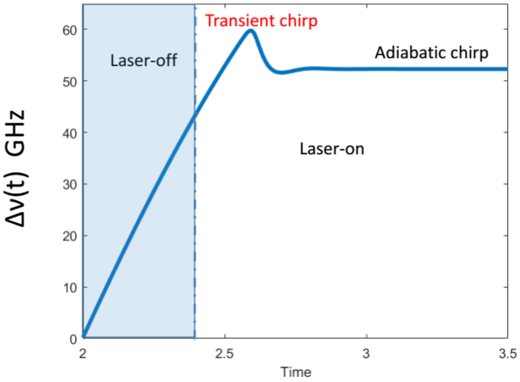
- The current at t = 2ns increases from zero to $I = 4I_{th}$ on and off the laser. ON=> Bit 1; OFF=>Bit 0
- The carrier density initially increases as the active-region reservoir is filled and we have only carriers loss due to non-radiative recombination and spontaneous emission. Therefore little photon density exists until the carrier density reaches its threshold value.
- At this point, stimulated recombination begins and it limits the increase in carrier density as soon as the stimulated emission becomes more and more relevant. This delay before the photon density turns on is called the "turn-on" delay of the laser.
- After a transient dominated by under-damped relaxation oscillations N_p will eventually reach the steady state value and N will clamp at the threshold value.
- We have under-damped response: ε was set to zero and the current step is not large enough.

Response to a current step: chirp

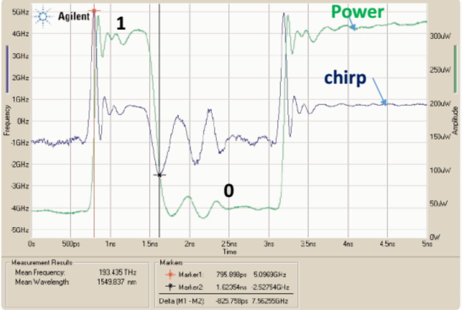
- The frequency chirp can be calculated as

$$\delta\nu(t) = \frac{\alpha_H}{4\pi}\frac{1}{P_O}\frac{dP_O(t)}{dt}$$

- The transient chirp depends on output power $P_O(t)$ and its variations



Chirp and spectrum Broadening

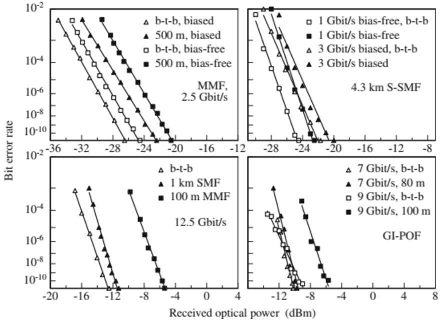


BER and Q

- In digital optical transmission, the bit error ratio is expressed as a function of the Q-factor by

$$BER = \frac{1}{2}\mathrm{erfc}(Q/\sqrt{2}), \quad Q \propto < P > / \sqrt{< \delta I_N^2 >}$$

with $< P >$ average power at the photodetector and $< \delta I_N^2 >$ variance of the current noise.



VCSELs advantages vs. edge emitting lasers

- low threshold currents (<1 mA!)
- minimized power consumption
- easier design of electronic driver circuits
- excellent digital modulation behavior for data rates >40 Gbit/s
- high power conversion efficiencies
- circular beam profiles with small divergence angles
- wide ambient temperature range (>+125 °C)
- complete testing and device selection on the wafer level
- very high reliability with projected lifetimes of the order of ten million hours at room temperature

Lasers damage

Catastrophic optical (mirror) damage

- We define as catastrophic optical (mirror) damage (COD, COMD), the power limit at which sudden, irreversible failure of a facet occurs.
  - The semiconductor material at the laser facet is melt and recrystallized because of the excessive heat, leading to an increased number of lattice defects.
  - The typical values for COD in industrial products range between 12 and $20\,\mathrm{MW\,cm^{-1}}$.
- At high optical power densities (50-100% of the COD): the atomic states at the semiconductor/air interface have energy levels within the band gap of the semiconductor.
  - Absorbed photons can lead to breaking of chemical bonds on the surface followed by oxidation which further accelerates the degradation.
  - Heating of the mirror causes the band gap to shrink in the warmer areas, leading to increased absorption: thermal runaway.

Catastrophic optical (mirror) damage

- This mechanism occurs, with lower degradation rates, for optical powers down to < 50% COD.
- A sudden failure mechanism, independent of optical power density, is caused by dark-line defects, i.e. propagating dislocation networks caused by nonradiative recombination carriers, deriving from material defects.
- Aging and effects of the environment increase light absorption at the surface.

Table 1. Semiconductor laser diode active-layer materials for emission at 808 nm.

	Sudden Failure	Typical Lifetime	Power at which COD occurs
GaAs (~60 Å)	Yes	8000 h	11 MW/cm^2
AlGaAs	Yes	4000 h	
InAlGaAs	No	5000 h	
InGaAsP	No	>5000 h	~18 MW/cm^2

Catastrophic optical (mirror) damage

- Many solutions have been proposed and are currently used to reduce these failures
  - The presence of aluminum in the active area is a critical parameter: AlGaAs QW lasers have a shorter lifetime and higher degradation rate than other laser sources.
  - Doping of the surface shifts the absorption wavelength in the proximity of the terminal facet.
  - Increasing the terminal waveguide leads to a reduction of the power density
  - Depositing the electrodes away from the facet prevents the injection of charge close to the facets.

Effects of radiation on Laser Diodes

- Laser diodes could conceivably be exposed to ionizing and particles radiations, which mainly generate defect in the semiconscious material.
- Radiation-induced defects produce energy levels in the band gap affecting the electrical properties of the semiconductors.
- Irradiation of laser diodes
  - speeds up aging characteristics
  - increases threshold current
  - shifts the lasing wavelength
  - decreases light output at constant current
  - increases turn-on time delays.
- In general, carrier lifetime can be written as

$$\frac{\tau_0}{\tau} = 1 + \tau_0 K \Phi$$

with τ_0/τ pre/post-irradiation carrier lifefime, K damage constant and Φ radiation fluence [cm^{-1}]

Effects of ionizing radiations

- Gamma irradiation is unlikely to cause significant degradation of performance in laser diodes at room temperature.
- When ionizing radiation (1 MeV γ rays from ^{60}Co) interacts with the semiconductor, it displaces bound electrons, producing electron-hole pairs.
- These primary electrons move through the material and generate secondary (Compton) electron cascades.
- If dopant impurities are present in the material, the electrons or holes may be captured at the impurity atom sites: charged defect sites are created, serving as nonradiative recombination centers
- The energy required to generate an electron-hole pair in the semiconductor GaAs is 4.8 eV
- In the case of high-power laser diode arrays, threshold current and differential quantum typically change < 10% for doses up to 4 Mrad of ^{60}Co γ rays.

Effects of neutrons radiations

- Neutrons are considerably more damaging than γ: the damage constant K is ≈ 100 times greater for neutron irradiation damage than for that caused by gamma irradiation.
- The collision of a neutron with the lattice can transfer a large amount of energy to a primary knock-on atom, which in turn can cause a dense cascade of several hundred displacements.
- This cluster of defects is thought to exist as a large disordered region with dimensions of a few hundred angstroms and to contain a high density of nonradiative recombination sites.
- Neutron irradiation reduces the quantum efficiency, increase the susceptibility of the laser diode to facet damage.
- A blue shift of the lasing wavelength has been observed after neutron irradiation

Effects of X-ray radiations

- Experiments and simulations were carried out to study the sensitivity of laser sources to X-ray radiations.
- Significant effects were observed at dose rates near 10 Trad s^{-1}.
- The laser diodes exhibited a 500 μs interruption of current and laser output in response to the radiation pulse. After the optical power recovered from the pulse, it oscillated above and below its initial value. The laser diodes also exhibited temporary turn-on effects from the off state.
- When increased shielding and shorter cables were used in the experiment, the effects were greatly reduced or eliminated. Therefore, the X-ray effects were attributed to electromagnetic pulse (EMP) or photoinduced currents on the cables to the laser diodes.

Radiation hardness

- "Good" lasers tend to be radiation insensitive since they tend to exhibit low threshold current, optimum heat sinking, low dependence on temperature, low carrier lifetime, high radiance and high initial light output.
- It has been reported that vertical cavity surface-emitting lasers (VCSELs) show excellent resistance to a variety of radiation conditions.
  - However, a recent Sandia report concluded that a GaAs-based VCSEL emitting at 850 nm underwent a 30% decrease in output power after being exposed to a fluence of 4.4×10^{13} cm from a fission neutron source.
- Quantum dot materials show enhanced radiation hardness as compared with edge-emitting QW lasers.

Further readings/references

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