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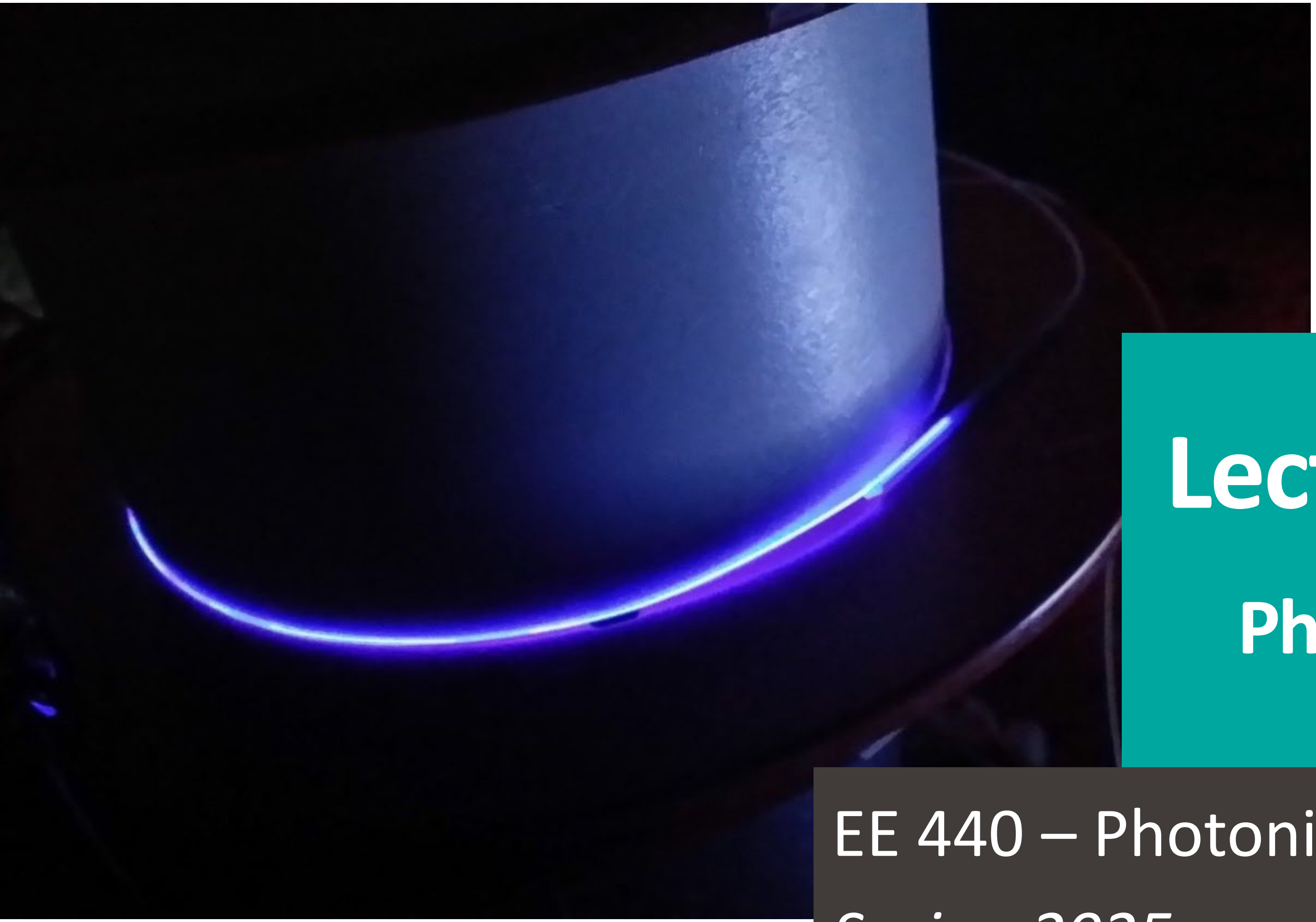

Lecture 2

Photonic Sources

EE 440 – Photonic systems and technology

Spring 2025

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Lecture 2 outline

Light matter interactions

- Einstein quantum theory of radiation
- Atomic transition
- Population inversion

P-N junction and light emitting diodes

- Characteristics
- Dynamic behavior

Semiconductor lasers

- Threshold and longitudinal laser modes
- Rate equation

Pulsed sources

Light-matter interactions

Laser history

Theoretical background of laser action developed by Einstein as early as 1916

1954: C.H. Townes et al. developed the MASER (Microwave Amplifier based on Stimulated Emission Radiation)

1958: A. Schawlow and C. H. Townes adapted the MASER to optical frequencies

1960: T.H. Maiman build the first laser (ruby laser)

Other Lasers (HeNe etc.) followed rapidly

Until the 1960s all light sources used in optics were based on *spontaneous emission*: signal comparable to *noise.*

With the *laser* it became possible to generate well defined optical wave functions

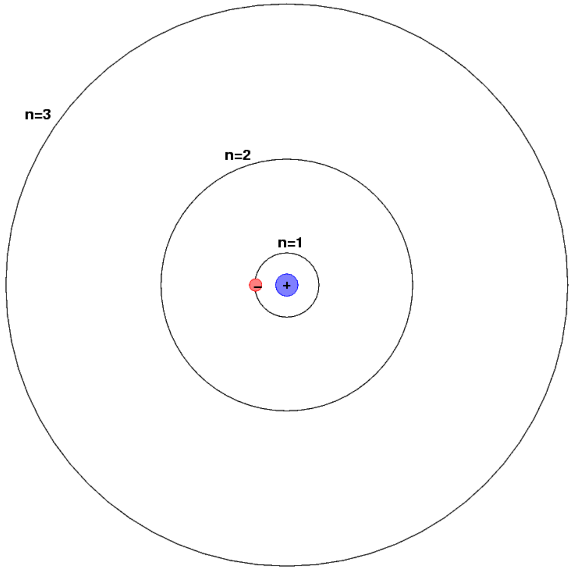
But what is responsible for this ?

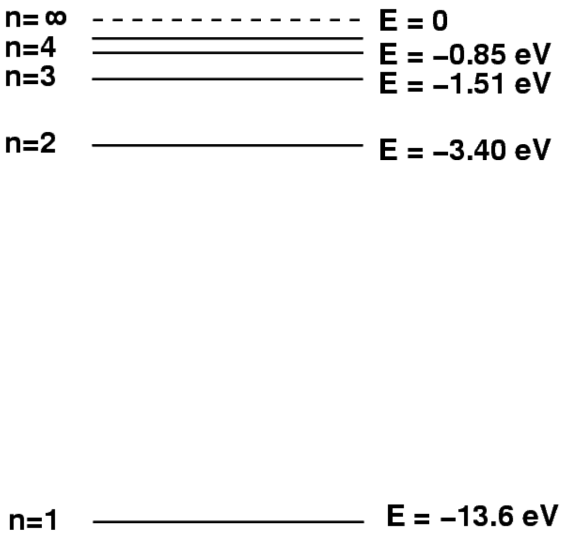
Let’s look at light – matter interactions

Energy levels

Matter contains electric charges:

- The electric field of light interacts with the electric charges in atoms, molecules, and solids.
- Interaction depends on the energy difference between two atomic energy levels.
- The allowed energy levels and energy bands are determined by the rules of quantum mechanics.





Energy levels occupation: Boltzmann distribution

Each atom/molecule continuously undergoes random transitions among its difference energy levels:

- Temperature T is the principal determinant of the energy-level occupancy.

In thermal equilibrium, at a fixed temperature T, the population ratio between two energy levels is given by:

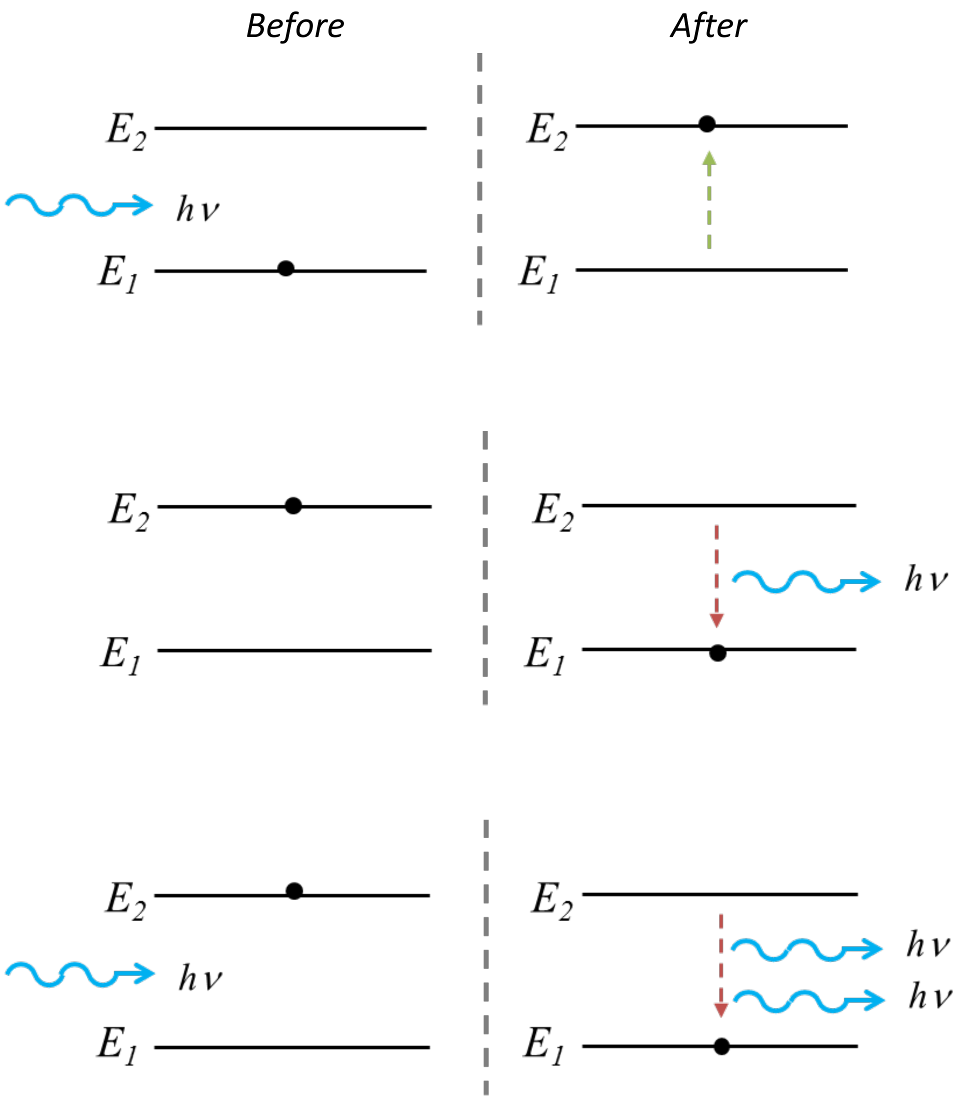
$$\frac{N_2}{N_1} = \exp\left(\frac{E_1 - E_2}{kT}\right)$$

Boltzmann distribution

N_i: number of atoms in level of energy E_i

k: $1.3806 \cdot 10^{-23}\ \mathrm{JK}^{-1}$ (Boltzman constant)

Einstein's quantum theory of radiation



Absorption

- Photon of energy $E_{ph} = h\nu = E_2 - E_1$ is incident on the matter
- Atom goes to excited state

Spontaneous emission

- Radiative recombination
- Photon spontaneously emitted with energy $E_{ph} = h\nu = E_2 - E_1$

Stimulated emission

- Incident photon causes radiative recombination
- Two photons with same characteristics are created

Atomic levels

Atomic levels and transitions may be considered in terms of:

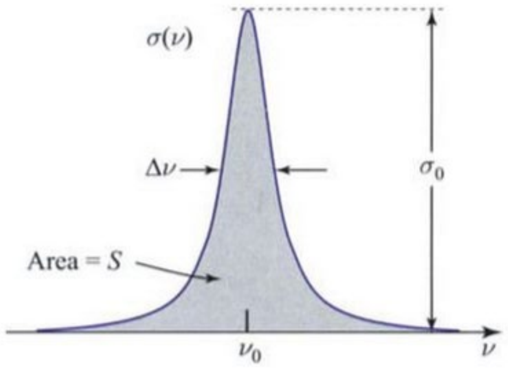
- Resonant frequency $\boldsymbol{\nu_0}$ between level m and l: $\nu_0 = \frac{(E_m - E_l)}{h}$
- Each level m has a lifetime $\boldsymbol{\tau_m}$: the inverse at the rate at which the population of that levels decays to all lower levels.
- Each excited level has a spontaneous lifetime $\boldsymbol{\tau_{sp}}$: inverse of the rate at which population of that level decays to all lower levels through radiation.
- Atomic transition about the resonance ν_0 are characterized by its transition cross section $\sigma(\nu)$(in cm^2): quantifies the likelihood of optically induced transition events.

Lineshape function

$\sigma(\nu)$ characterizes the interaction of the atom with radiation, has an area:

$$S = \int_0^\infty \sigma(\nu)\, d\nu \approx \frac{\lambda^2}{8\pi\tau_{sp}}$$

Transition strength (cm^2-Hz)

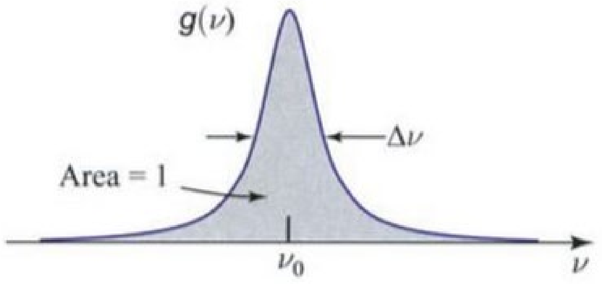


- The shape of $\sigma(\nu)$ governs the relative magnitude of the interaction with photons of different frequencies

The lineshape function $g(\nu)$ is the normalized cross-section

$$g(\nu) = \frac{\sigma(\nu)}{S}$$

Lineshape function (Hz^{-1})



Probability density for transitions

Spontaneous emission

- Probability density (s^{-1}) of spontaneous emission W_{sp} from a level is inversely proportional to its lifetime τ_{sp}.

$$W_{sp} = \frac{1}{\tau_{sp}}$$

Probability density of spontaneous emission

Stimulated emission and absorption

- For (nearly) monochromatic light at frequency ν and intensity I, the probability density $W_{sp} = W_{ab} = W_i$ depends on the mean photon flux ϕ:

$$W_i = \phi\sigma(\nu)$$

Probability density of induced transition

$$\phi = \frac{I}{h\nu}$$

Mean photon flux (photons/cm^2-s)

Lineshape function broadening

Real spectral lines are broadened usually following a Lorentzian profile

- Energy levels are not infinitely sharp: from the uncertainty principle

$$\Delta E \Delta t = \Delta E \tau_m \sim \hbar$$

Uncertainty principle

- A photon emitted in a transition from this level to the ground state will have a range of possible frequencies

$$\delta\nu \sim \frac{\Delta E}{h} \sim \frac{1}{2\pi\tau_m}$$

Natural linewidth

- The corresponding spread between two levels of lifetime τ_1 and τ_2 :

$$\Delta\,\nu = \frac{1}{2\pi}\left(\frac{1}{\tau_1} + \frac{1}{\tau_2}\right)$$

Lifetime broadening linewidth

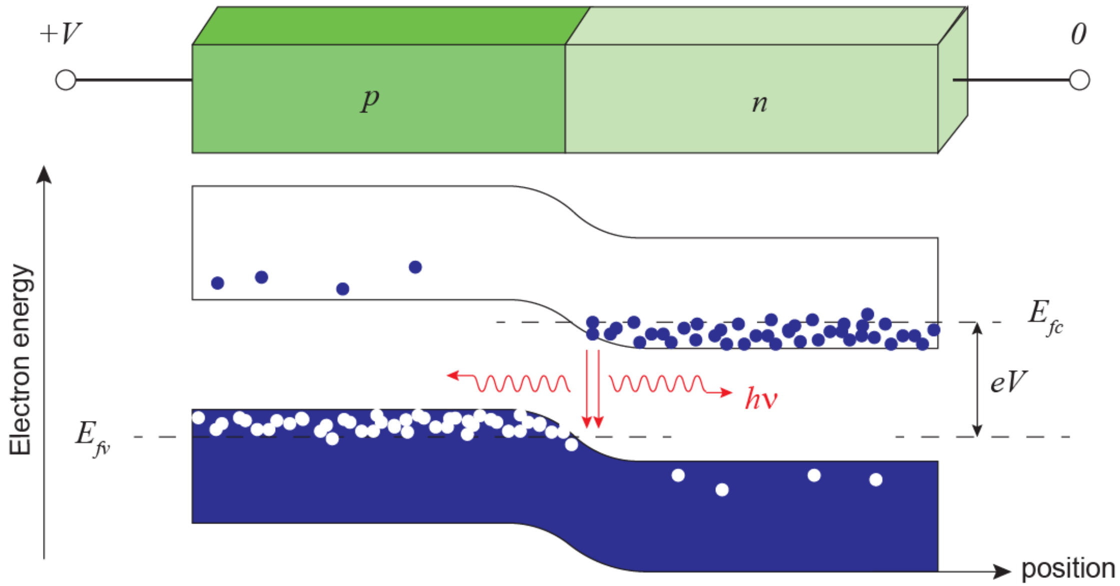
Light emitting diodes

Semiconductor sources

Light can be emitted from a semiconductor materials as a result of electron-hole recombination:

- Materials capable of emitting such light do not 'glow' at room temperature.
- Need an external source of energy (i.e. pumping) to produce electron-hole pairs.

Most convenient way is to forward bias a p-n junction: light emitting diode (LED)



Light emitting diodes (LED)

The number of emitted photons is proportional to the number of injected carriers in the junction:

- At given current i, the carrier-injection rate is: $\frac{i}{e}$
- Given internal efficiency η_{int}, the rate of photon generation: $\eta_{int}\frac{i}{e}$
- The internally generated power is therefore: $P_{int} = \left[\eta_{int}\frac{i}{e}\right]h\nu$
- Given an extraction efficiency η_e , the emitted power P_e is:

$$P_e = \eta_e P_{int} = \eta_e \eta_{int} \frac{h\nu}{e} i$$

LED output optical power

External efficiency and responsivity

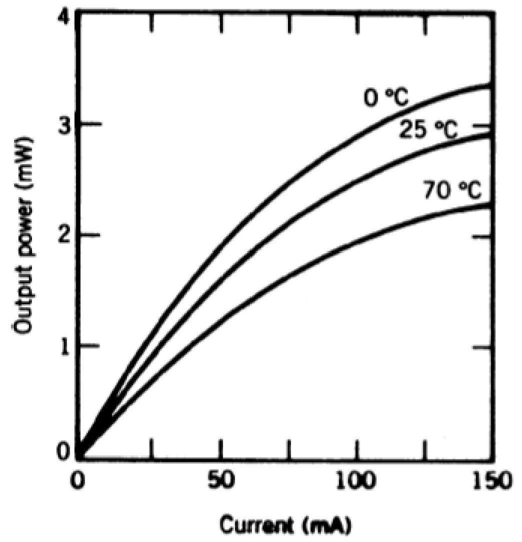
$$\eta_{ext} = \eta_e \eta_{int}$$

External efficiency

$$R = \eta_{ext} \frac{h\nu}{e}$$

Responsivity (W/A)

$$P_e = Ri$$



Output power is first proportional to the injected current

- … but bends at higher currents because of increasing internal losses
- Internal quantum efficiency also decreases with temperature

Quantum efficiences

The external quantum efficiency η_{ext} is defined by:

$$\eta_{ext} = \frac{\text{number of output photons from the diode } (\text{s}^{-1})}{\text{number of inject electrons into the diode } (\text{s}^{-1})} = \frac{\text{optical power}/h\nu)}{\text{diode current}/e}$$

- Internal efficiency for LEDs ranged between 50% to 100%
- Extraction efficiency for properly designed devices can go up to 50%
- External efficiency is thus typically 50%

The external differential quantum efficiency η_{edqe} is defined by:

$$\eta_{edqe} = \frac{\text{increase in \#output photons } (\text{s}^{-1})}{\text{increase in \#injected electrons } (\text{s}^{-1})} = \frac{\text{change in optical power}/h\nu)}{\text{change in diode current}/e}$$

The external power efficiency η_{epe} is defined by: $\eta_{epe} = \frac{\text{Optical output power}}{\text{Electrical input power}} = \frac{P_e}{iV}$

Spectral distribution

The spectral distribution is governed by the spectrum of the spontaneous emission rate (electroluminescence):

- Under condition of weak pumping, spectral intensity achieved its peak value at:

$$h\nu_p = E_g + \frac{k_B T}{2}$$

Peak frequency

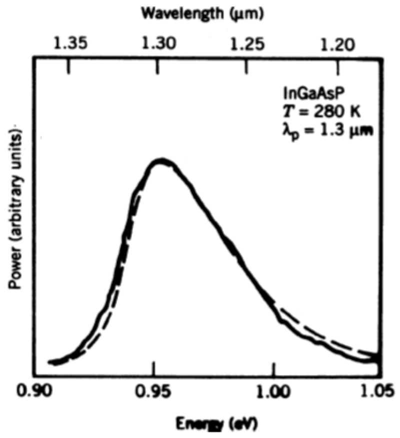
- The full width at half max (FWHM) of the spectral intensity is:

$$\Delta\nu \approx 1.8\frac{k_B T}{h}$$

Spectral width (Hz^{-1})

$$\Delta\lambda \approx 1.45\lambda_p^2 k_B T$$

Spectral width (μm)
with λ_p in μm and k_bT in eV



LASERS

We want ‘stimulated’ emission …

LEDs are based on spontaneous emission: light is chaotic

In order to have well defined wavefunctions, stimulated emission has to be the prevalent process:

LASER – Light amplification through stimulated emission of radiation

- However stimulated emission and absorption of a transition have the same probability density!
- Stimulated emission ‘starts’ from the upper level of the transition
- Absorption ’starts from the lower level of the transition
- To favor stimulated emission there needs to be more atoms in the excited state: population inversion is necessary.

When emission is more likely than absorption: *net optical gain* ensues.

Optical gain γ

Let's consider a lasing transition between lower level a and upper level b

- When the injected carrier density (N_i) in the active layer is such that $N_b > N_a$, population inversion is realized and the active region exhibits optical gain $\gamma(\nu)$.

$$\gamma(\nu) = \sigma(\nu)(N_b - N_a)$$

$$\gamma(\nu) = \sigma(\nu)N$$

Optical gain (cm^{-1})

$\sigma(\nu)$: transition cross section

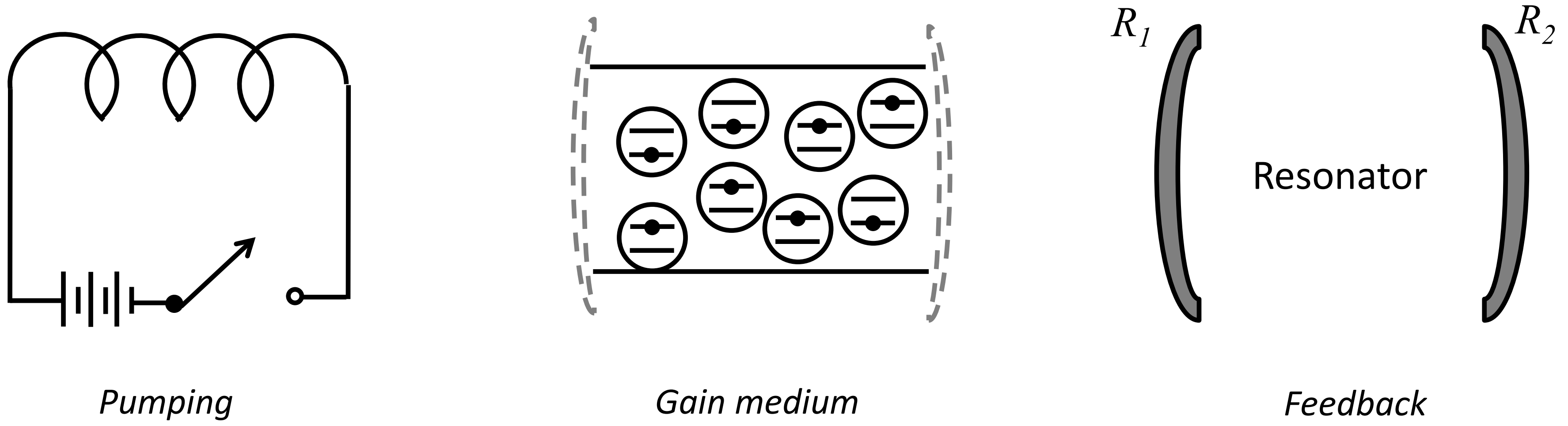
N : population difference between the lasing levels

An input signal propagating inside the active layer of length L would then be amplified with a single pass gain G:

$$G = \exp(\gamma L)$$

Single pass gain

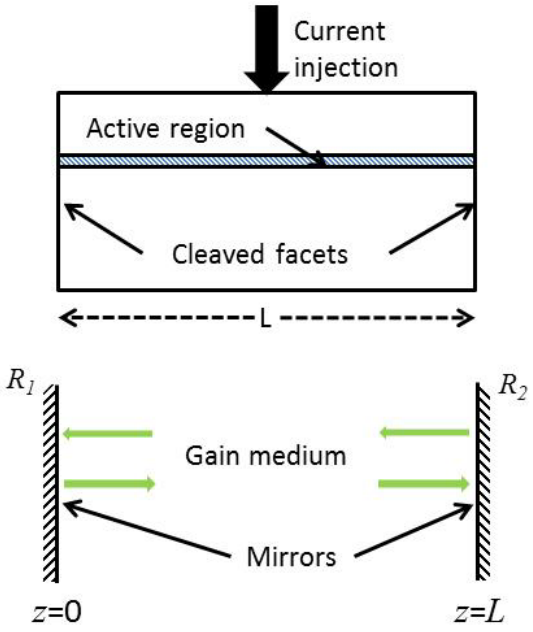
Encouraging stimulated emission



Lasing conditions in an optical resonator

To make a laser, a resonator can be formed by placing a gain medium between two end facets

- The gain medium provides a distributed power optical gain γ to the optical mode
- Facets have power reflectivity R_1 and R_2
- Resonator contributes to distributed power losses due to imperfections (α_s)



Electric field in the cavity at a point z is $E(z)$:

$$E(z) = E_0 \exp\left[j(\beta z - \omega t) + z\frac{\gamma - \alpha_s}{2}\right]$$

After one round trip, we have:

$$E(z+2L) = E_0\sqrt{R_1 R_2}\exp\left[j(\beta(z+2L) - \omega t) + (z+2L)\frac{\gamma - \alpha_s}{2}\right]$$

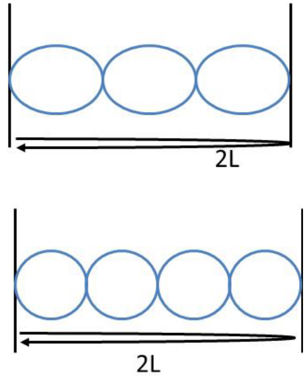
$$\mathfrak{I} = \frac{\pi\sqrt{|r|}}{1-|r|}$$

The limiting condition for lasing is: $E(z+2L) = E(z)$

Conditions for lasing (1)

Let's consider the phase condition:

- After a round trip wave must be back in phase with itself:



$$\beta L = m\pi$$

$$\frac{2\pi\nu n}{c_0} L = m\pi$$

$$\nu = \nu_m = m\frac{c_0}{2nL}$$

- ν_m are the lasing longitudinal modes.
- These definite discrete frequencies are equally spaced by: $\delta\nu = \frac{c_0}{2nL}$

Emission only possible for these cavity standing waves at given central frequencies ν_m

Conditions for lasing (2)

Let's consider the amplitude condition:

- Gain must compensate for losses:

$$\gamma(\nu) = \underbrace{\alpha_s + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)}$$

$$\alpha_r = \alpha_s + \alpha_m$$

- α_r represents the total loss of energy (or number of photons) per unit length.
- Is related to the photon lifetime inside the cavity since $\alpha_r c$ is the loss of photon/s

$\tau_p = \frac{1}{\alpha_r c}$: photon lifetime

Threshold condition for laser: $\gamma(\nu) = \alpha_r$

Gain vs material gain

At laser threshold and beyond, the power gain γ must equal the cavity loss α_r

The power gain γ is not the same as the material gain γ_m

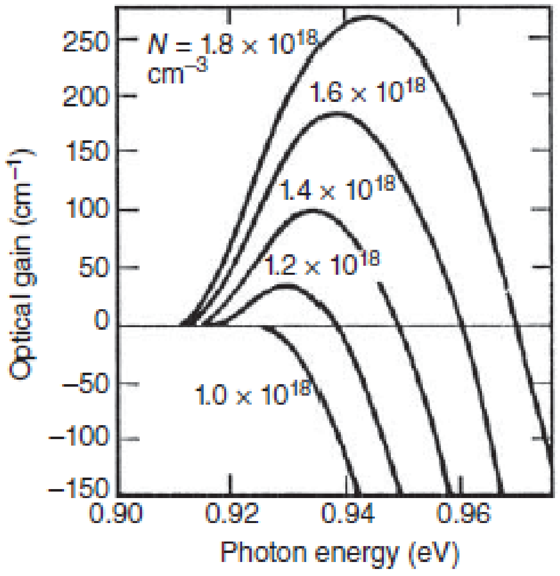
- The optical mode extends beyond the active layer
- The gain exists only inside the active layer

As a result, the gain is decrease by the confinement factor Γ

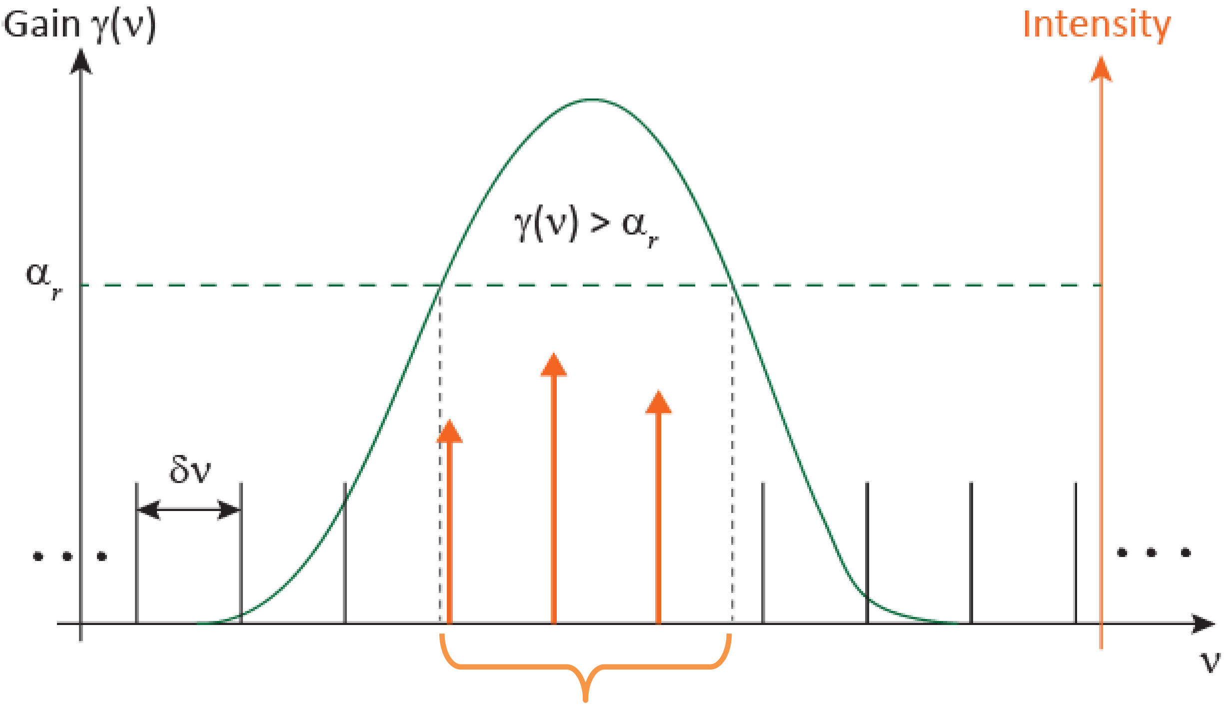
$$\gamma = \Gamma \gamma_m$$

- Typical values are less than 0.4

Gain spectra at several carrier densities for a 1.3 um InGaAsP active layer



Laser modes

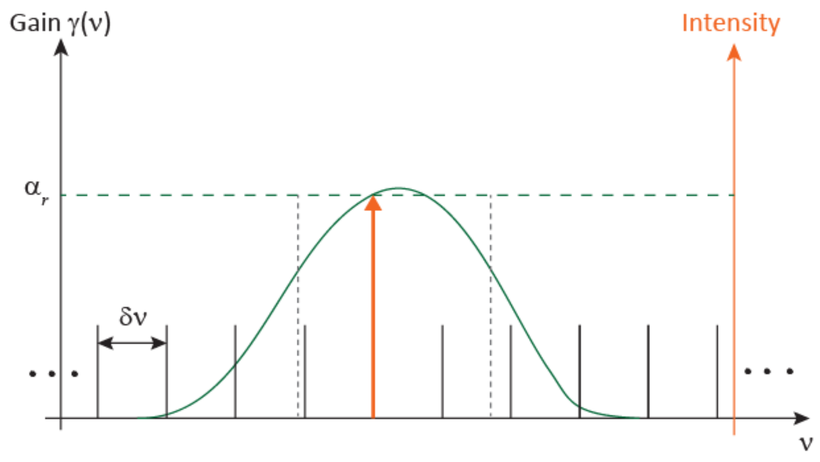


Modes satisfying $\gamma(\nu) > \alpha_r$ start to grow

Gain broadening

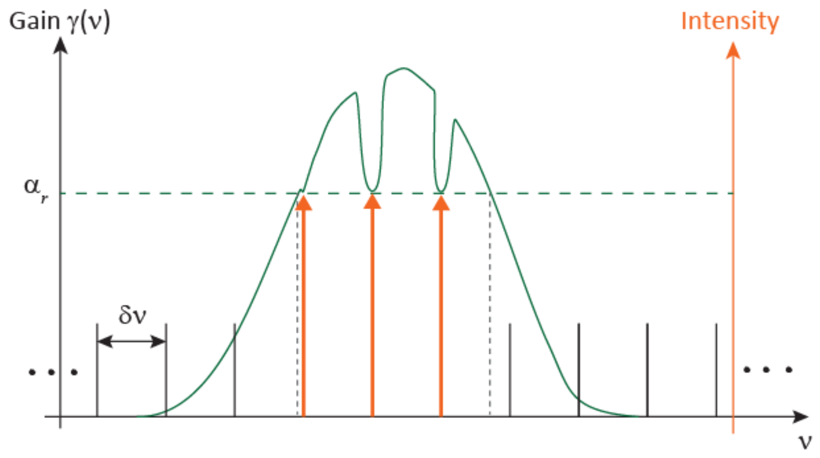
Homogeneous gain saturation:

- All atoms behave the same
- Shape of gain spectrum is not modified: mode with highest gain wins it all
- Single mode lasing



Inhomogeneous gain saturation:

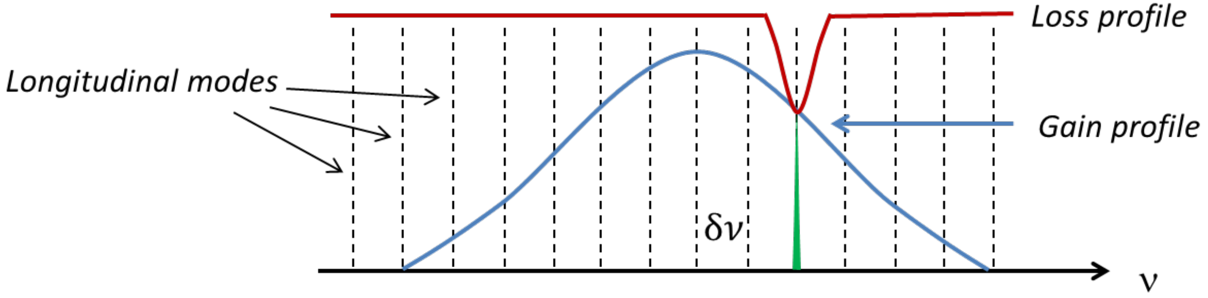
- Different atoms interact with different λ
- Saturation is stronger around the modes: gain is quenched only at these positions
- Multimode lasing



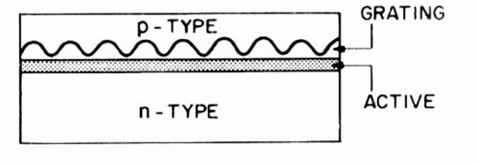
When lasing: $\gamma(\nu) = \alpha_r$

Single mode lasers

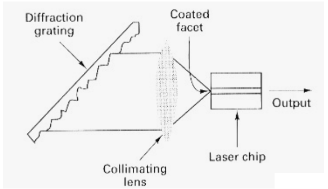
Wavelength dependent cavity loss → single-mode lasing



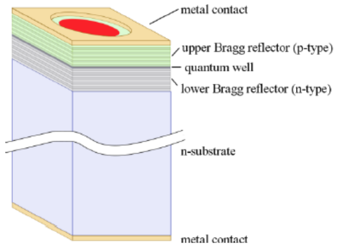
- Distributed feedback laser (DFB) – most common
  - Wavelength selective grating in the cavity
  - Can be temperature tuned (~ 5nm)



- External cavity laser (ECL)
  - Uses a frequency selective element outside cavity
  - Widely tunable (~ 50 nm)



- Vertical cavity surface emitting laser (VCSEL)
  - Light output orthogonal to the substrate



Dynamics

The rate equations

Describe the static and dynamic behavior of semiconductor lasers

- Let $P(t)$ be the photon density in an active volume V (for eg. in cm^{-3})
- Let $N(t)$ be the electrons density in an active volume V (for eg. in cm^{-3})
- Assume electrical pumping and single-mode operation

$$\frac{dP(t)}{dt} = aN(t)P(t) + R_{spon} - \frac{P(t)}{\tau_p}$$

- $aN(t)P(t)$: Stimulated emission
- R_{spon}: Spontaneous emission into lasing mode
- $\frac{P(t)}{\tau_p}$: Photon loss rate

$$\frac{dN(t)}{dt} = \frac{I}{eV} - \frac{N(t)}{\tau_c} - aN(t)P(t)$$

- $\frac{I}{eV}$: Electron supplied by pumping
- $\frac{N(t)}{\tau_c}$: Spontaneous transition
- $aN(t)P(t)$: Stimulated emission

a: quantity associated with probability that carrier will capture a photon and give rise to stimulated emission
τ_c: carrier lifetime
τ_p : photon lifetime

Steady state solutions

Interested in the steady state behavior

- All time transients have died
- Time differentiation yields zero ($\frac{d}{dt} = 0$)
- Assume spontaneous emission R_{spon} is negligible

$$\frac{dP(t)}{dt} \approx aN(t)P(t) - \frac{P(t)}{\tau_p}$$

$$\frac{dN(t)}{dt} = \frac{I}{eV} - \frac{N(t)}{\tau_c} - aN(t)P(t)$$

$$P(t)\left(\frac{aN(t)\tau_p - 1}{\tau_p}\right) = 0$$

$$\frac{I}{eV} - \frac{N(t)}{\tau_c} - aN(t)P(t) = 0$$

There are *three regions of operation* depending on the current I

CW steady state solution – region 1

– For small current:

$$P(t)\left(\frac{aN(t)\tau_p - 1}{\tau_p}\right) = 0$$

$$aN(t)\tau_p < 1$$

$$\therefore P(t) = 0$$

$$\frac{I}{eV} - \frac{N(t)}{\tau_c} - aN(t)P(t) = 0$$

$$\frac{I}{eV} - \frac{N(t)}{\tau_c} = 0$$

$$\therefore N(t) = \frac{\tau_c}{eV} I$$

CW steady state solution – region 2

– At lasing threshold:

$$P(t)\left(\frac{aN(t)\tau_p - 1}{\tau_p}\right) = 0$$

$$aN(t)\tau_p = 1$$

$$\therefore N_{th} = \frac{1}{a\tau_p}$$

$$\therefore P(t) \approx 0$$

$$\frac{I}{eV} - \frac{N(t)}{\tau_c} - aN(t)P(t) = 0$$

$$\frac{I_{th}}{eV} - \frac{N_{th}}{\tau_c} = 0$$

$$\therefore I_{th} = \frac{eV}{\tau_c} N_{th}$$

CW steady state solution – region 3

– Above threshold:

$$P(t) > 0$$

$$P(t)\left(\frac{aN(t)\tau_p - 1}{\tau_p}\right) = 0$$

$$aN(t)\tau_p = 1$$

$$\therefore N(t) = N_{th} = \frac{1}{a\tau_p}$$

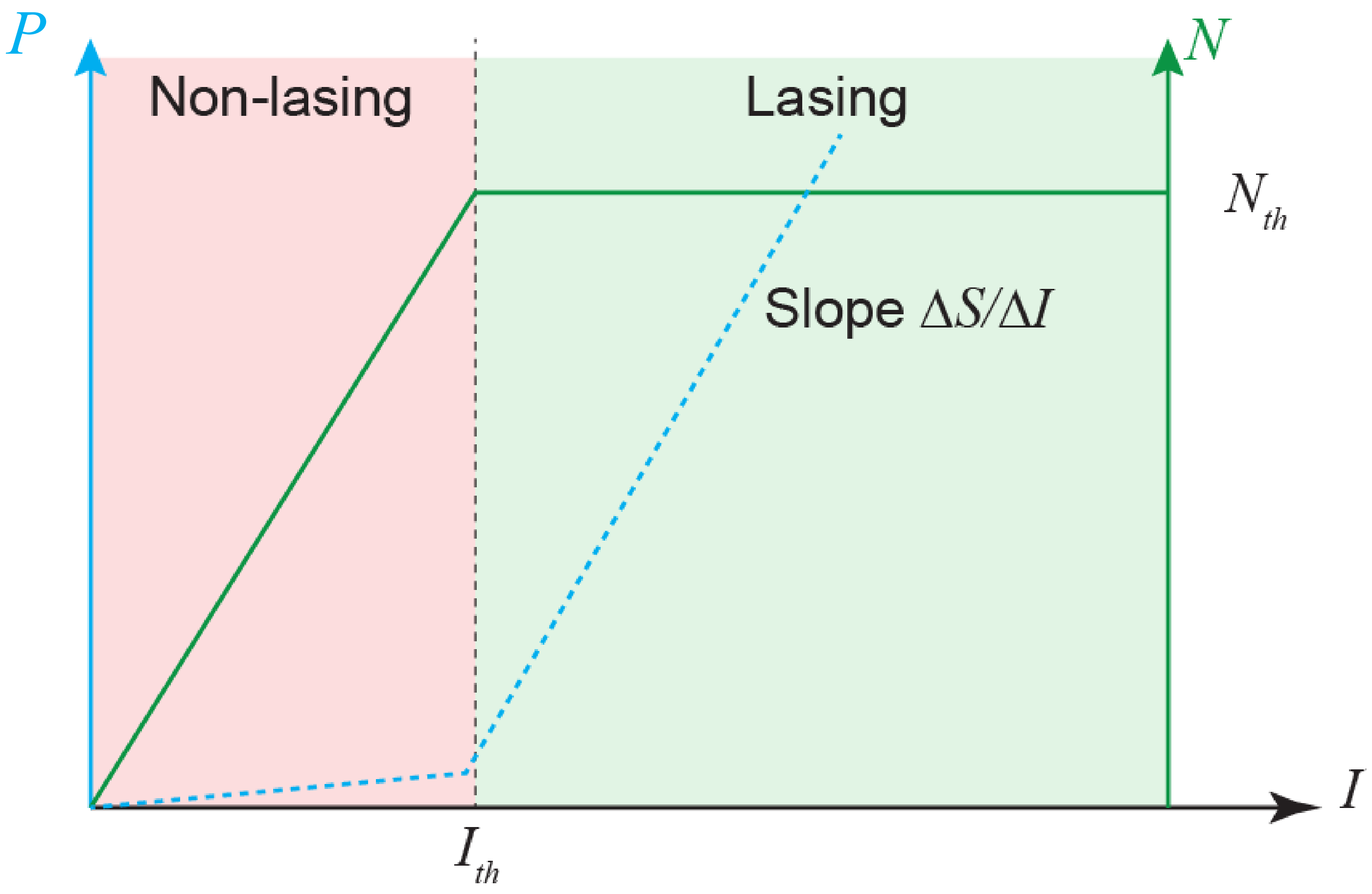
$$\frac{I}{eV} - \frac{N(t)}{\tau_c} - aN(t)P(t) = 0$$

$$P(t) = \frac{I\tau_p}{eV} - \frac{1}{a\tau_c}$$

$$P(t) = \frac{\tau_p}{eV}\left(I - \frac{eV}{a\tau_c\tau_p}\right)$$

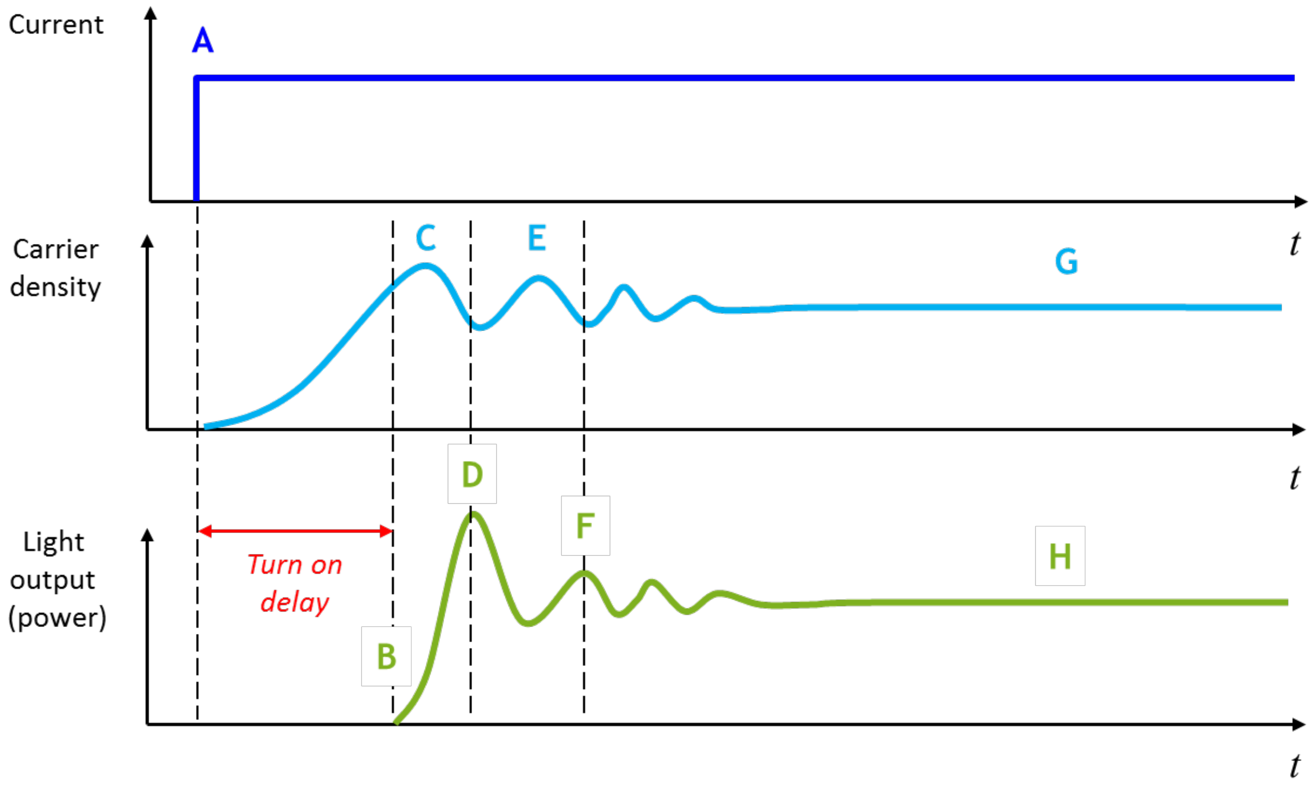
$$\therefore P(t) = \frac{\tau_p}{eV}(I - I_{th})$$

CW steady state solutions



Laser dynamics: turn on delay

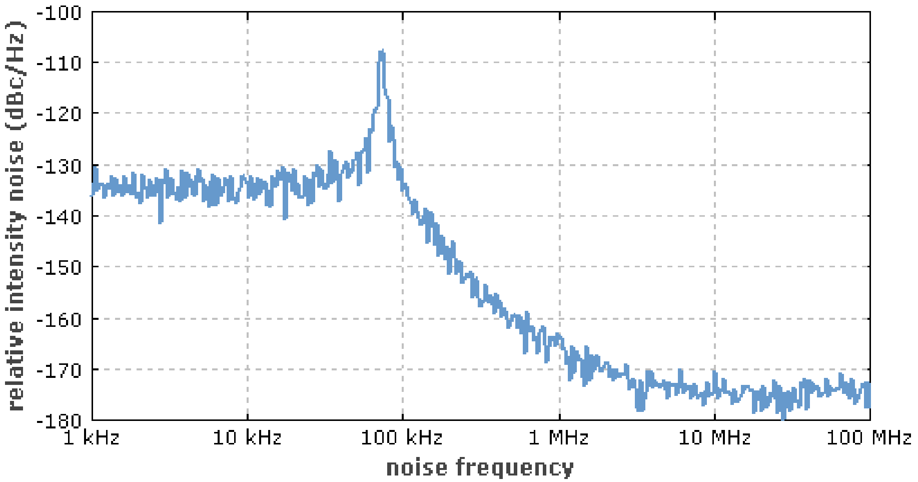
There is typically a time delay between the initial injection of current and the generation of light



Laser dynamics: relative intensity noise (RIN)

The power emitted by a semiconductor laser fluctuates around a steady state value

- Spectrum of these fluctuations can be measured on an electrical spectrum analyzer
- RIN can be statistically described with a power spectral density (PSD) which depends on the noise frequency
- Unit typically in dBc/Hz: dB relative to the carrier in a 1 Hz noise bandwidth



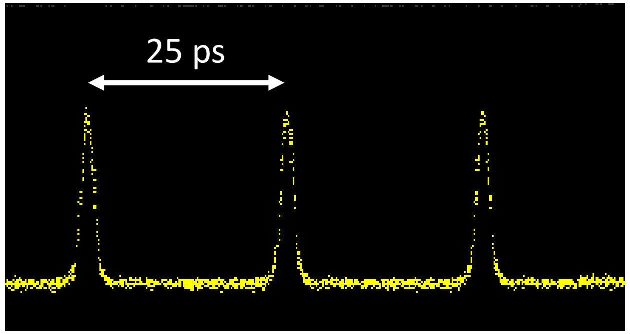
- Laser RIN exhibits a characteristic peak related to the relaxation oscillations.

Pulsed sources

Pulsed source

A pulsed laser emits light in short burst rather than as a continuous wave

- This can be achieved directly in the cavity by Q-switching, modelocking or gain switching



Key characteristics of such sources:

- Repetition rate (f_{rep}): the number of pulses per second (Hz)
- Pulse duration $\Delta\tau$ or τ_{FWHM}: time width if a single pulse (typically fs – ns)
- Pulse energy (E_p): energy contained in a single pulse
- Average power (P_{avg}): time averaged output power (measured by a power meter)
- Peak power (P_{peak}): maximum power during the pulse
- Time-bandwidth product: fundamental limit on pulse compression given a spectral bandwidth $\Delta\nu$

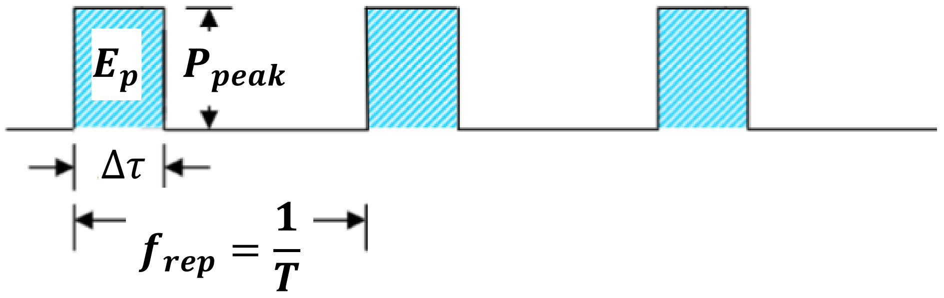
$$\Delta\nu\Delta\tau \approx 0.44 \text{ (Transform limited Gaussian pulse)}$$

$$\Delta\nu\Delta\tau \approx 0.315 \text{ (Transform limited sech}^2\text{ pulse)}$$

Power and energy in pulsed laser

Pulse energy $E_p = \frac{P_{avg}}{f_{rep}}$

- Example $P_{avg} = 1$ W and $f_{rep} = 100$ MHz



Peak power: $P_{peak} = \frac{E_p}{\Delta\tau}$

- Example: $\Delta\tau$ = 50 fs

Average power: $P_{avg} = E_p f_{rep} = P_{peak}\left(\frac{\Delta\tau}{T}\right)$

Ultrashort pulses enables extremely high peak powers even with moderate average power

The tradeoff is that they require a broader bandwidth

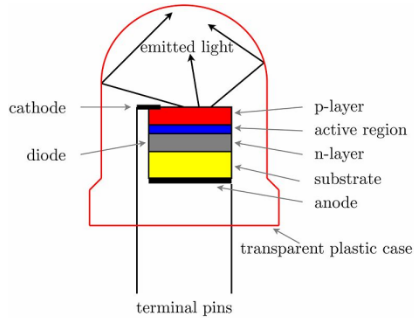
- Note: light is still coherent ! The different frequency components in the pulse maintain a **fixed phase relationship** with each other, allowing for a well-defined and reproducible pulse shape.

Summary

Summary of light emitting diodes (LED)

A forward biased p-n junction emits light through spontaneous emission (electroluminescence): it is the simplest form of an LED

- LED output is spontaneous emission, generated by radiative recombination of electrons and holes in active region of diode under forward bias.
- The semiconductor material is direct-bandgap to ensure high quantum efficiency, often III-V semiconductors.
- An LED emits incoherent, non-directional, and unpolarized spontaneous photons that are not amplified by stimulated emission.
- The emission thus spreads over a broad spectrum (30 – 100 nm)
- An LED does not have a threshold current. It starts emitting light as soon as an injection current flows across the junction.
- Direct modulation bandwidth is relatively low



Summary of laser

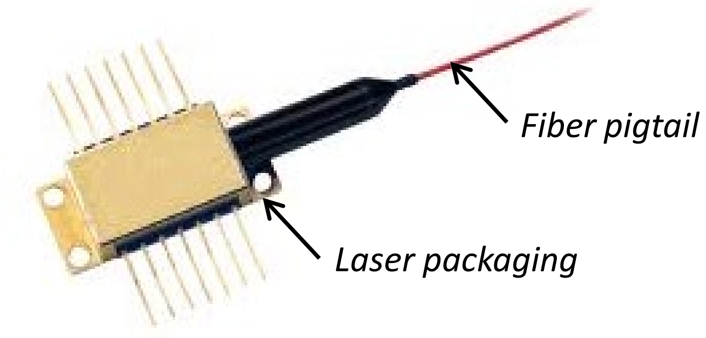
The lasing process depends on:

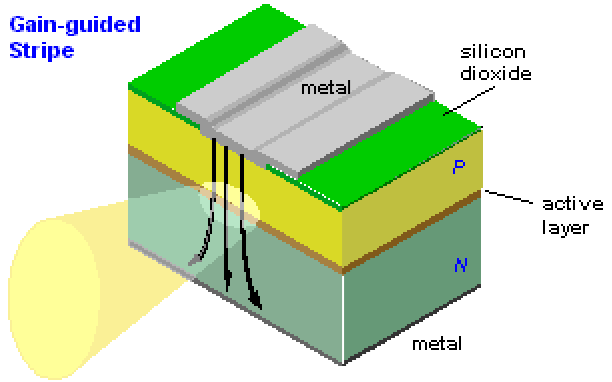
- Population inversion achieved by pumping, between two appropriate levels in the laser medium
- Seed photons from spontaneous emission of proper energy and direction initiates stimulated emission
- An optical cavity confines and directs the growing number of photons; need to have gain compensating loss
- Total round trip phase shift must be a multiple of 2π: lasing occurs
- Couple light out of one mirror to produce the external beam

Semiconductor lasers

A semiconductor laser is a semiconductor optical amplifier that has an optical feedback: they emit light through stimulated emission

- The injected current is sufficiently large to provide optical gain
- The optical feedback is usually implemented by cleaving the semiconductor material along its crystal planes
- The sharp refractive index difference between crystal ($n \approx 3.5$) and surrounding air ($n = 1$) causes the cleaved surfaces to act as reflectors (Fresnel reflections)
- The laser has a threshold current : if the optical gain is not large enough to compensate for the feedback losses, the photon population cannot build up





Lasers in optical communications

Depending on the application, the desired characteristics of the optical source might vary.

For modern optical communication characterized by its need for high speed, high quality transmission, the quality of the optical source is critical

- Low noise operation
- Narrow linewidth for good stability with external modulator
- Single mode operation to limit dispersion effects
- Stability for long term operation
- Wavelength tunable for wavelength agile networks
- Good output power

Source types

	LED	Laser diode	Single mode laser diode
Spectral width (nm)	20 - 100	1 - 5	<0.2
Rise time (ns)	2 – 250	0.1 - 1	0.05 - 1
Modulation bandwidth (MHz)	<300	2000	6000
Coupling efficiency	Very low	Moderate	High
Compatible fiber	Multimode	Multimode/single mode	Single mode
Temperature sensitivity	Low	High	High
Circuit complexity	Simple	Complex	Complex
Costs	Low	High	Highest
Primary use	Short distances Low data rates	Long distances High data rates	Very long distances Very high data rates