EEE 6212
Semiconductor Materials

Lecture 24: LASER principles

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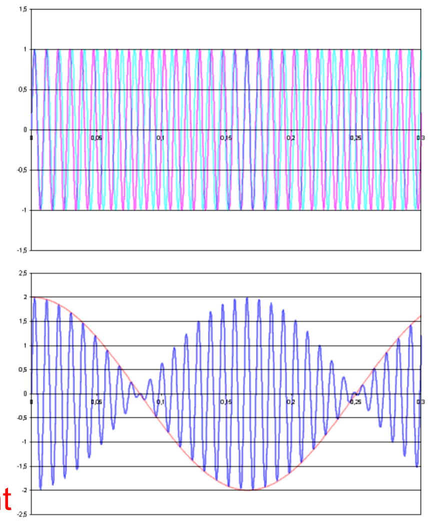
- interference and coherence
- temporal and spatial coherence
- spontaneous emission
- stimulated emission (needs population inversion)
- feedback (needs resonating cavity)
- gain
- types of semiconductor solid-state LASERS

interference and amplitude modulation

superimpose
$\boldsymbol{E}_1 = E_0 \exp(j\omega_1 t)$ and
$\boldsymbol{E}_2 = E_0 \exp(j\omega_2 t)$



get $\boldsymbol{E}_1 + \boldsymbol{E}_2$
$= E_0[\exp(j\omega_1 t) + \exp(j\omega_2 t)]$
$= E_0 \exp\{j[(\omega_1+\omega_2)/2 + (\omega_1-\omega_2)/2]t$
$+ E_0 \exp\{j[(\omega_1+\omega_2)/2 - (\omega_1-\omega_2)/2]t$
$= 2E_0 \cos[(\omega_1-\omega_2)t/2] \exp j[(\omega_1+\omega_2)t/2$
slow amplitude modulation × fast oscillation

intensity for slow detector:
$\langle E^2 \rangle = 4\, E_0^2 \cos^2[(\omega_1-\omega_2)t/2]$

will consider source as monofrequent
with $\Delta\omega = (\omega_1-\omega_2)/2$ if measurement time is $\tau \approx \pi/\Delta\omega$: temporal coherence

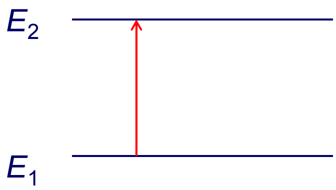
coherence

temporal coherence time: $\tau \approx \pi/\Delta\omega$
A monofrequent wave without any broadening $\Delta\omega$ would be perfectly temporally coherent.

similarly:
spatial coherence length: $x \approx \pi/\Delta k$
A wave of fixed wavevector $\underline{\boldsymbol{k}}$ ($\Delta\underline{\boldsymbol{k}}=0$) would be spatially coherent.
Often, this is written in terms of angles: $\Delta\Omega = \lambda^2/\Delta A$, where ΔA is the area of the light source. A perfectly spatially coherent wave would come from a single, perfect point ($\Delta A=0$).

absorption

consider transitions between **two** discrete energy levels E_1 and E_2 that are occupied by N_1 and N_2 electrons, respectively:



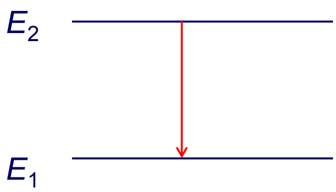
probability for absorption of photon by atom in ground state E_1:

$dN_1/dt = -B_{12} N_1 \rho_{12}$

with Einstein coefficient B_{12} for induced absorption and spectral energy density ρ_{12} of the radiation

spontaneous emission

consider transitions between two discrete energy levels E_1 and E_2 that are occupied by N_1 and N_2 electrons, respectively:



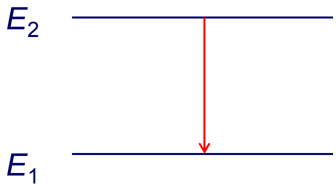
probability for spontaneous emission of photon by excited atom which returns to ground state by itself, without external influence:

$dN_2/dt = -A_{21} N_2$

with Einstein coefficient $A_{21} = 1/\tau_{21}$ for spontaneous emission. This spontaneous emission is isotropic and can therefore often be neglected.

stimulated emission

consider transitions between two discrete energy levels E_1 and E_2 that are occupied by N_1 and N_2 electrons, respectively:



probability for stimulated emission of photon by atom in excited state E_2 caused by external radiation field:

$dN_2/dt = -B_{21} N_2 \rho_{21}$

with Einstein coefficient B_{21} for induced or stimulated emission.

photon generation rate in 2-level system

Einstein could show that $B_{21}=B_{12}$ (without degeneration) and
A_{21}/B_{12}= energy × spectral modal density $=hf \times 8\pi f^2/c^3 = 8\pi\, hf^3/c^3$.

The density of states, N_i, in thermodynamic equilibrium obeys the Fermi-Dirac (or, at elevated temperatures, the Boltzmann) statistics:
$N_i \propto \exp[-E_i/(kT)]$, hence
$N_2/N_1 = \exp[-(E_2 - E_1)/(kT)]$

Note for $E_2>E_1$ at given temperature, that always $N_2<N_1$.

Define $\Delta N=N_2-N_1$. Hence, $\Delta N<0$.

Number of photons generated per length unit dz in time dt=dz/c:
$dQ/dz = dN_2 - dN_1 = B_{21} N_2 \rho_{21}\, dz/c - B_{12} N_1 \rho_{21}\, dz/c = B_{21} \Delta N \rho_{21}/c < 0$

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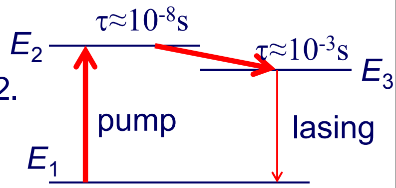
3- or 4-level systems

$dQ/dz = B_{21}\Delta N\, \rho_{21}/c < 0$
means it is impossible to get more photons out by amplification in thermodynamic equilibrium. The physical reason is that the ratio of probabilities for absorption to induced emission is always ≥1.

dQ/dz will only be >0 if $\Delta N > 0$, i.e. we need **population inversion.**
For this, need at least a 3rd, long lived (metastable) energy level, E_3.
$N_1+N_2+N_3=N$
$N_2 \approx 0$, because this state decays rapidly.
Hence, inversion means we need $N_3 > N/2$.



If a fourth level, E_4, between E_3 & E_1 is involved and lasing occurs for the transition E_3->E_4, inversion will occur **automatically** if E_4 is not normally thermally occupied. **All semiconductor interband LASERS are actually 4-level systems: pumping occurs from anywhere in the valence to anywhere in the conduction band; $E_3=E_C$; $E_4=E_V$**

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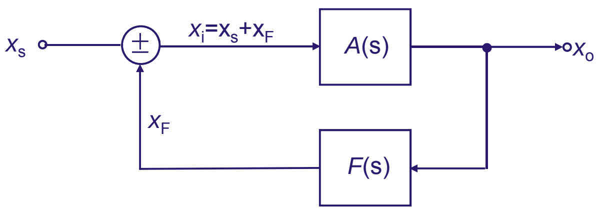
feedback theory: loop gain and total gain



signal: x_s
input: $x_i=x_s+x_F$
output: $x_o=A(s)\,x_i$
feedback: $x_F=F(s)x_o$
loop gain: AF
total gain: $A/(1-AF)$

Consider an inverting amplifier where x_s can be either a voltage or a current signal to be amplified. **$A(s)$ denotes the frequency dependent amplification factor and $F(s)$ the feedback**. Then we have:

$$\left.\begin{array}{l} x_i=x_s+x_F \\ x_o=A(s)\,x_i \\ x_F=F(s)\,x_o \end{array}\right\} \quad x_o=A(s)[x_s+F(s)x_o], \text{ hence gain: } \boxed{G(s)=x_o/x_s=A(s)/\,[1-\underbrace{A(s)F(s)}_{\text{loop gain}}]}$$

for large loop gain $A(s)F(s)>>1$: $G \approx A/(AF)=1/F(s)$ depends on feedback, rather than on the actual amplifier.
For LASERS: if $AF \to +1$, i.e. loop gain reaches unity, then $G \to \infty$

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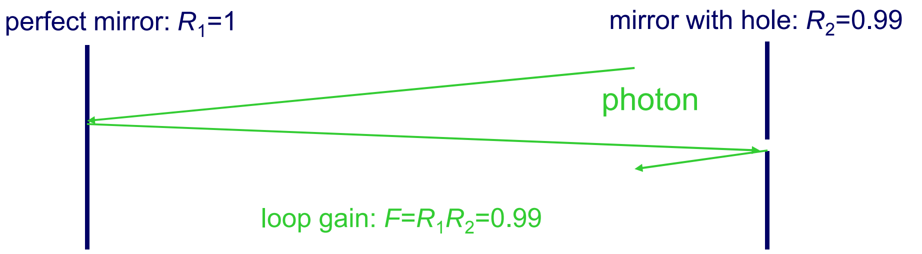
feedback in a simple LASER

If a nearby photon with energy ~E_g causes recombination by stimulated emission, this will generate another photon of the same frequency, travelling in the same direction, with the same polarisation and phase as the first photon. This means that stimulated emission causes gain in an optical wave (of the correct wavelength) in the injection region, and the gain increases as the number of electrons and holes injected across the junction increases.



Feedback in a light amplifier consists of partially transmissive mirrors that create a **resonating cavity**. In the example above, R describes the reflectivity of the mirrors. Only 1% of the light reaching the right mirror is output.

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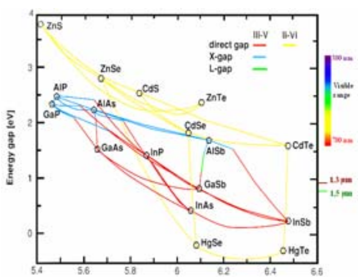
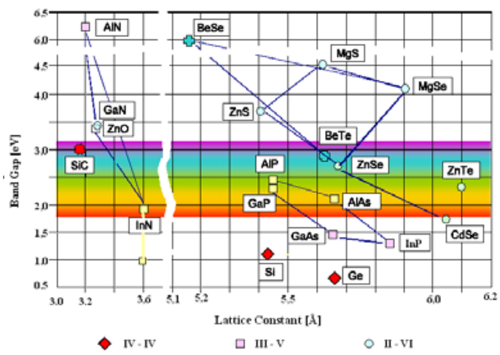
semiconductor band-gaps

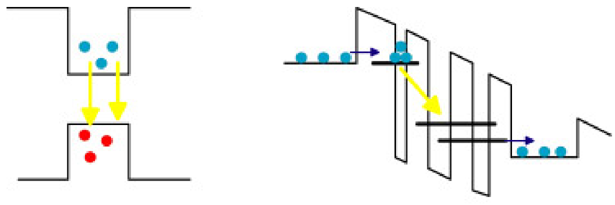
The spontaneous and stimulated emission processes are vastly more efficient in direct band-gap semiconductors than in indirect band-gap semiconductors; therefore GaAs rather than Si is commonly used for laser diodes.





source: U Kiel

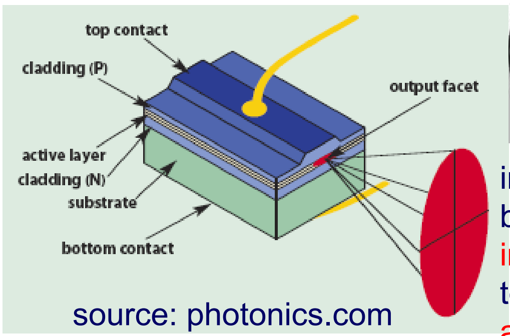
overview of semiconductor LASER types

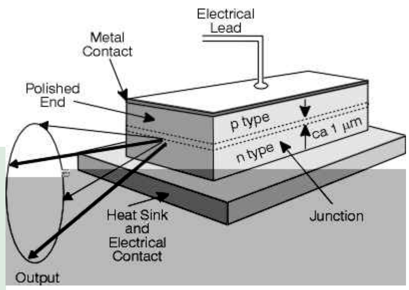


Interband Laser

Intersubband Laser

edge emitting LASER

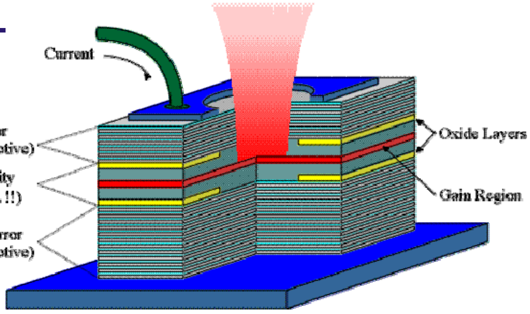




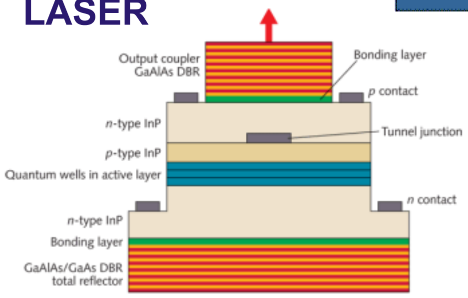
inject carriers into a forward biased pn-diode, induce interband transitions from E_c to E_v and use a cleaved facet as partially reflective mirror (other facet is metal coated to provide perfect mirror)

VCSEL

Vertical
Cavity
Surface
Emitting
LASER



source: CNR, Italy

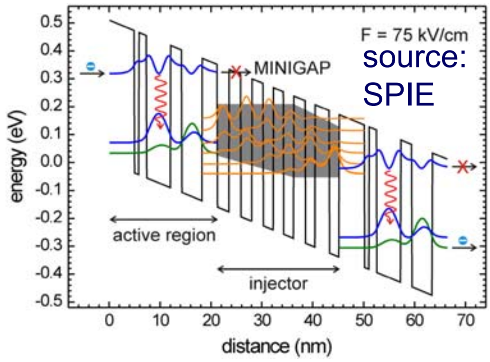


source: EPFL/Laser Focus World

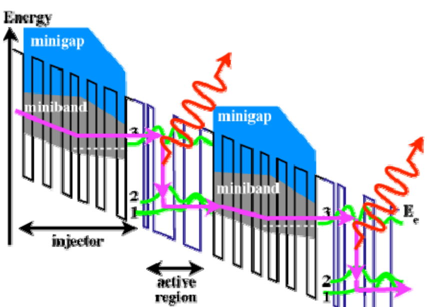
inject carriers into a quantum well, induce interband transitions from E_c to E_v and use multilayers as Distributed Bragg Reflector (DBR) mirrors, the top having a hole for the output beam

QCL

Quantum
Cascade
LASER



source: SPIE



source: DJ Paul, U Glasgow

inject electrons into a multiple quantum well (MQW) with **very** thin barriers so wave-functions in adjacent wells overlap; when 1 e^- moves through the MQW it can produce **many** low energy photons by inter-subband transitions