Escola Tècnica Superior d'Enginyeria de Telecomunicació de Barcelona

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

FIBER-OPTIC COMMUNICATIONS

JOAN M. GENÉ BERNAUS

OPTICAL COMMUNICATIONS GROUP
www.tsc.upc.edu/gco

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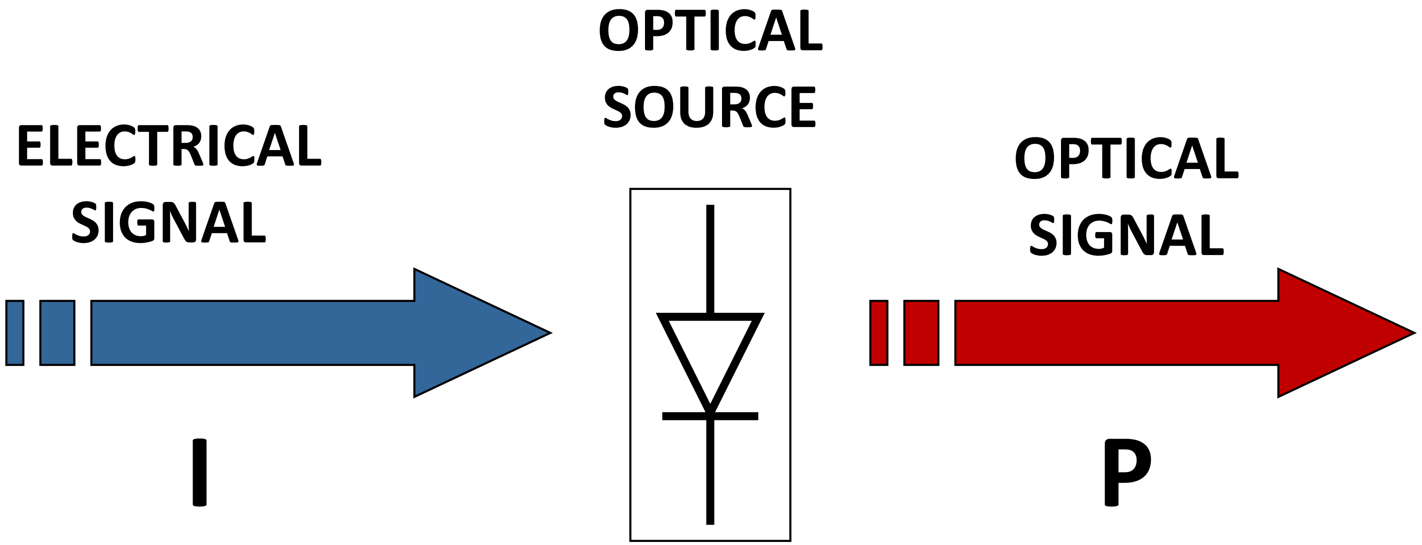
INTRODUCTION TO OPTICAL SOURCES

INTRODUCTION TO OPTICAL SOURCES



QUADRATIC CONVERSION

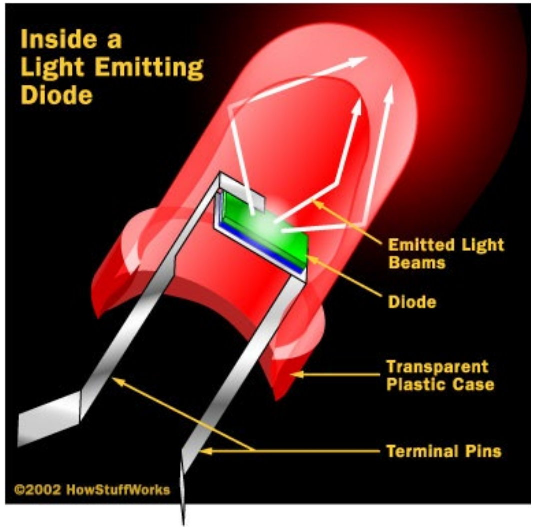
$$I \propto P$$

General Aspects

TYPES AND APPLICATIONS

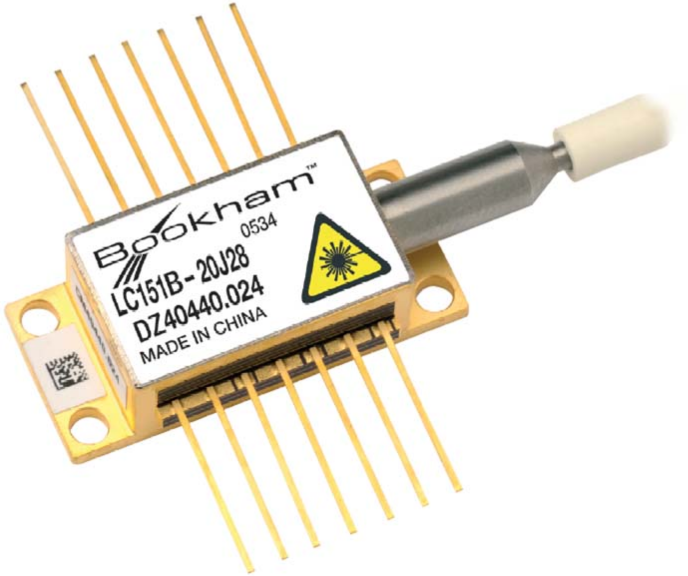
LED

- ❑ Visible → visualization
- ❑ near IR → telecom



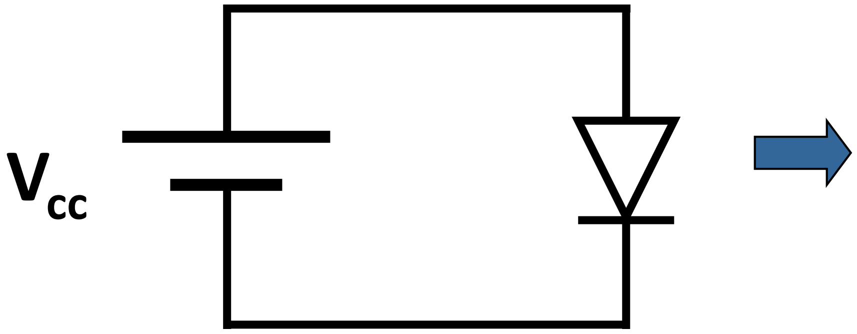
LASER DIODE

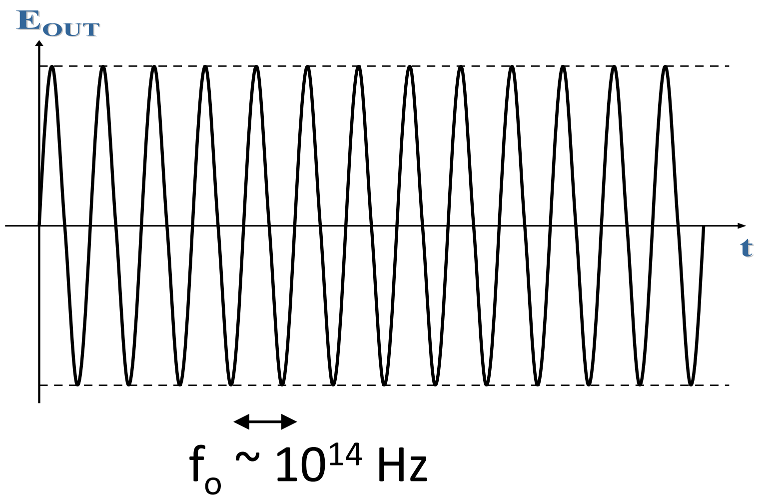
- ❑ Visible
  - → industry
  - → medicine
  - → space telecom
- ❑ near IR → telecom



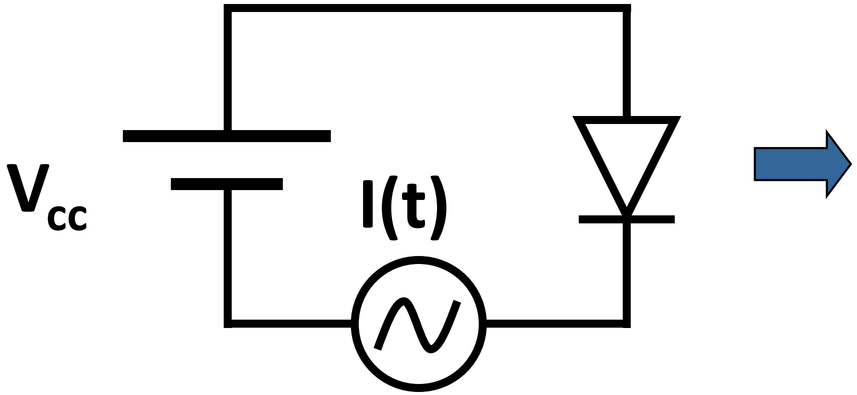
General Aspects

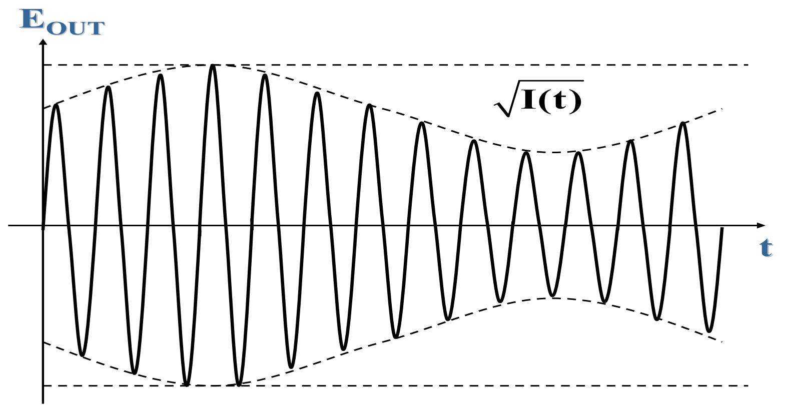
Continuous Wave (CW)





Direct Modulation (DM)





General Aspects

DESIRABLE CHARACTERISTICS

- ✓ EMISSION FREQUENCY
- ✓ HIGH E/O CONVERSION EFFICIENCY
- ✓ FIBER COMPATIBILITY (COUPLING)
- ✓ WORKING TEMPERATURE AND STABILITY
- ✓ HIGH SPECTRAL PURITY (LASER)
- ✓ LINEAR LIGHT-CURRENT RESPONSE
- ✓ HIGH MODULATION SPEED
- ✓ SMALL SIZE AND CONSUMPTION (INTEGRATION)
- ✓ REDUCED COST

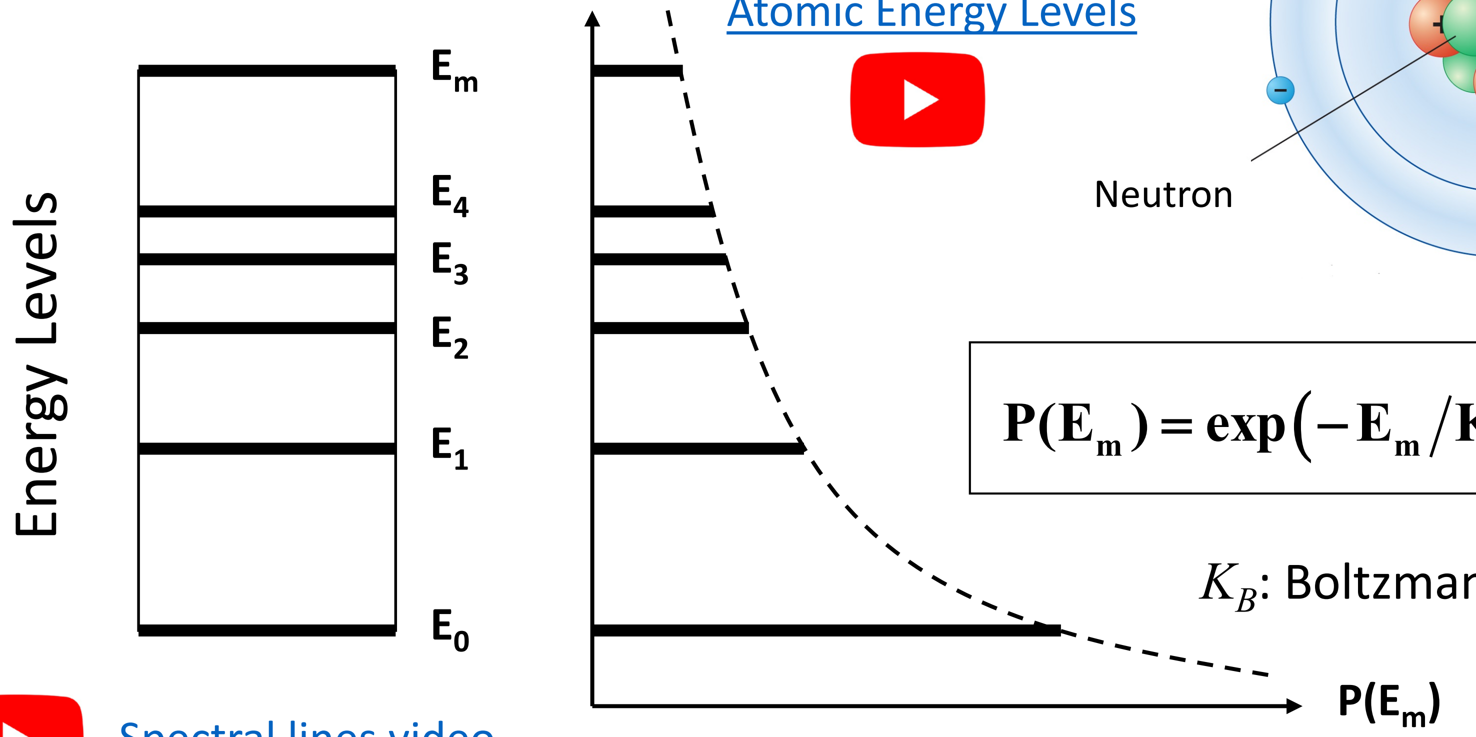
LIGHT-MATTER INTERACTION

Light-Matter Interaction

Atomic / Molecular Energy Levels

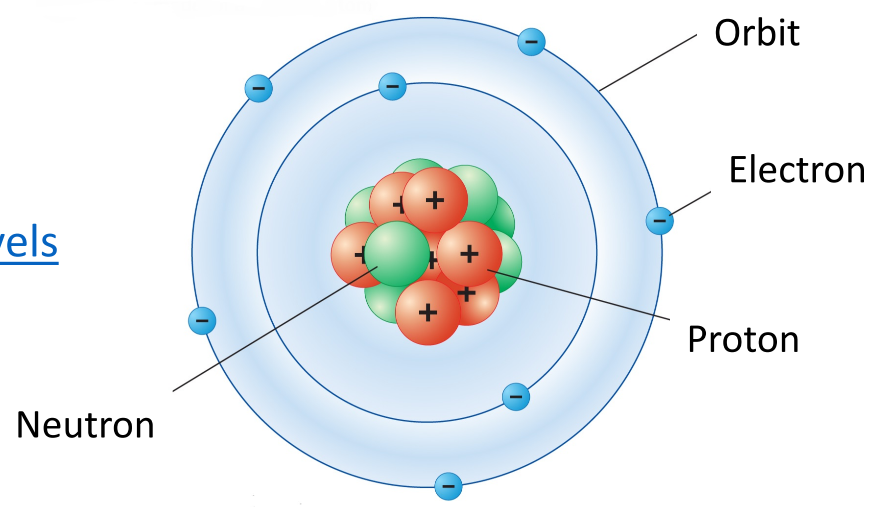
"The energy level of an isolated atom/molecule is discrete due to Pauli's Exclusion Principle.

[Atomic Energy Levels](#)



[Spectral lines video](#)

Bohr atomic model of a nitrogen atom
www.britannica.com/science/Bohr-model



$$P(E_m) = \exp\left(-E_m / K_B T\right)$$

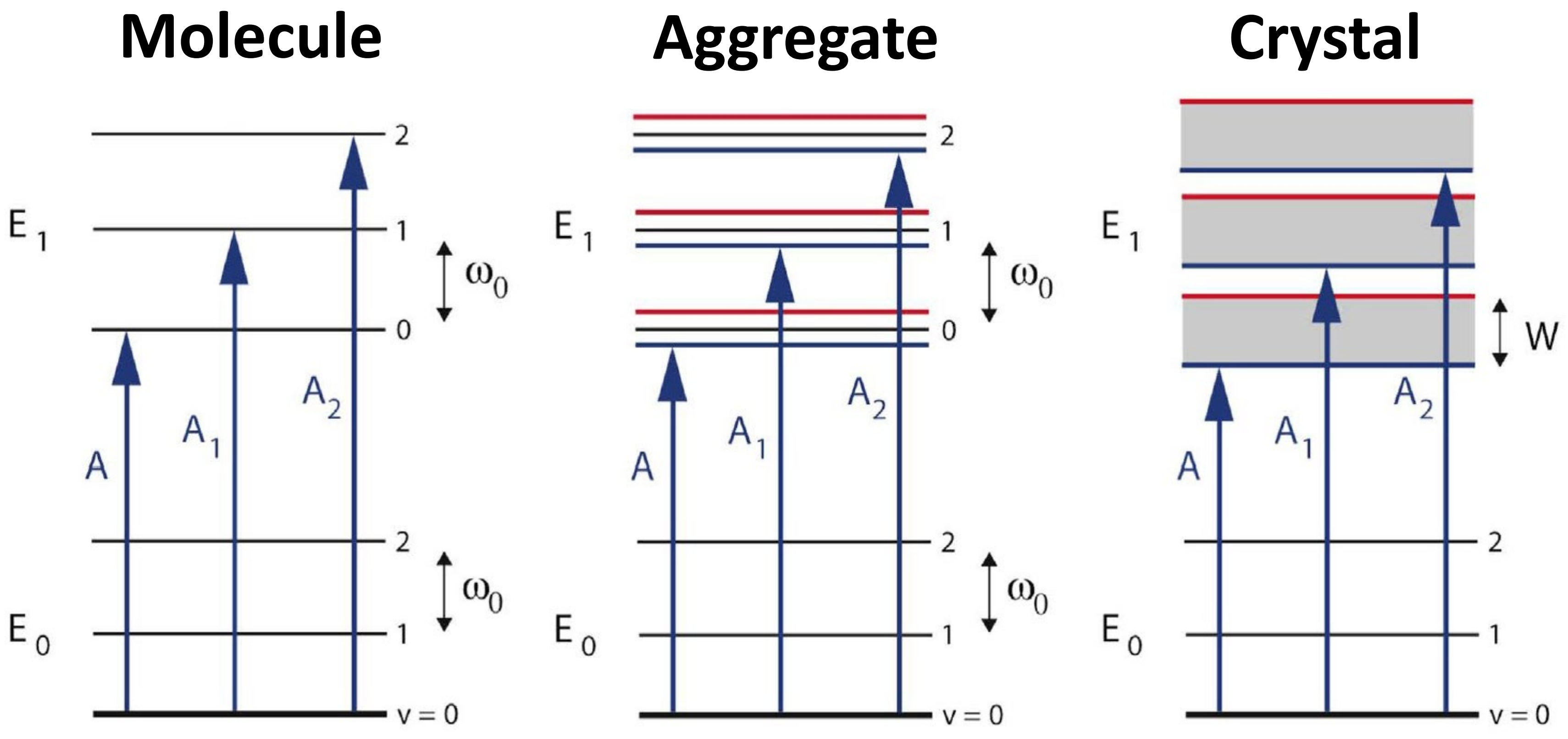
Boltzmann Statistics

K_B: Boltzmann Ct. ($1.38 \cdot 10^{-23}$ J/K)

Light-Matter Interaction

Compounds Energy Levels

When considering compounds, the influence of neighboring molecules unfolds new energy sublevels. Apart from the original electronic levels, some new kinetic energy levels appear.



https://www.nature.com/articles/srep32620

Light-Matter Interaction

Light Absorption / Emission Processes

"Any given material shows a particular light absorption characteristic. Some of them, under specific conditions, have the capacity of light emission".

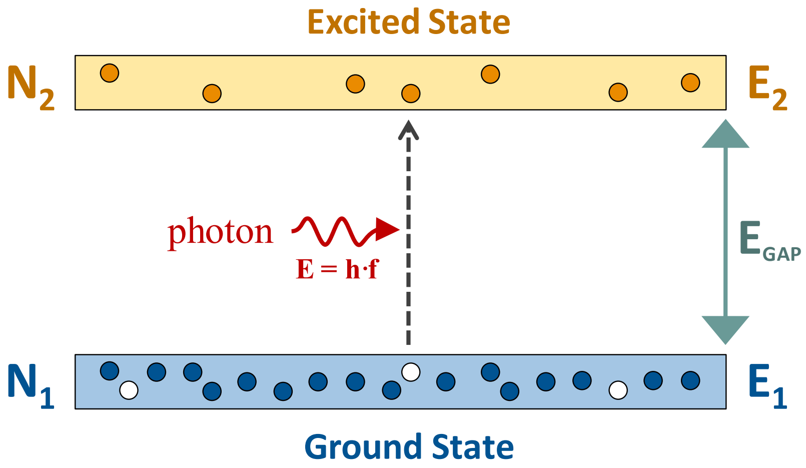
$hf \rightarrow$ photon energy

$hf \approx E_2 - E_1 = E_g$ (Energy Gap)

h: C. Planck ($6{,}63 \cdot 10^{-34}\ J \cdot s$)

f: light frequency

(STIMULATED) ABSORPTION



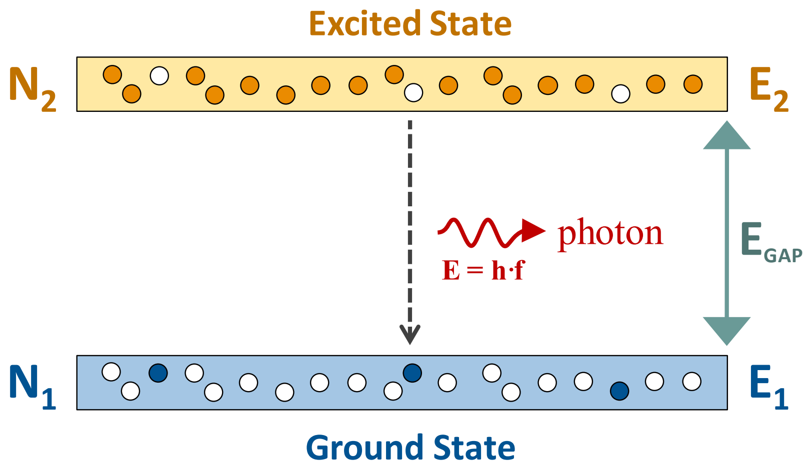
"The incident photon is absorbed by an electron which increments its energy level"

⇩

Photodetectors

Light-Matter Interaction

SPONTANEOUS EMISSION



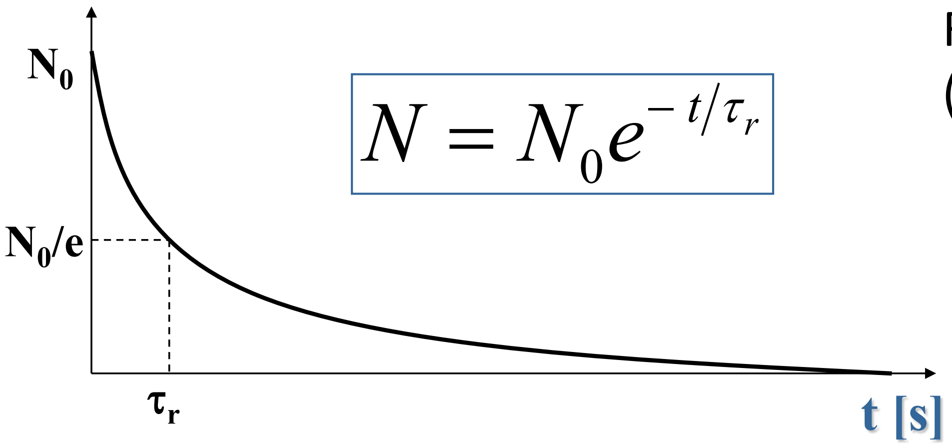
"An excited electron releases energy in the form of a photon with random frequency, phase, polarization, and direction"

⇩

Incoherent light (LED)

(Bose-Einstein statistics)

No. of excited electrons [N]



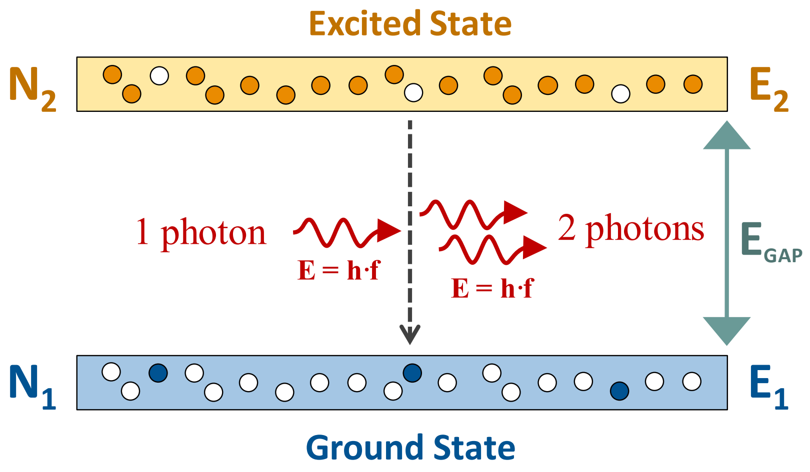
$$N = N_0 e^{-t/\tau_r}$$

Recombination Lifetime (Exponential Distribution) ➡ $pdf = \dfrac{e^{-t/\tau_r}}{\tau_r}$

τ_r: Carrier Lifetime → **"Average time to return to ground state"**

Light-Matter Interaction

STIMULATED EMISSION



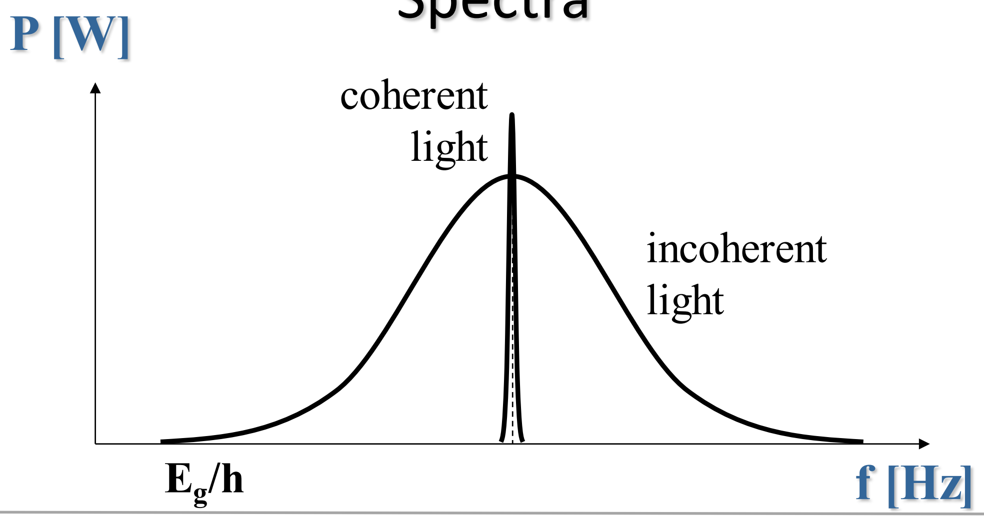
"An incident photon forces an excited electron to release its energy in the form of a new photon with exactly the same frequency, phase, polarization, and direction"

⇩

Coherent Light (LASER)

(Poisson Statistics)

Spectra

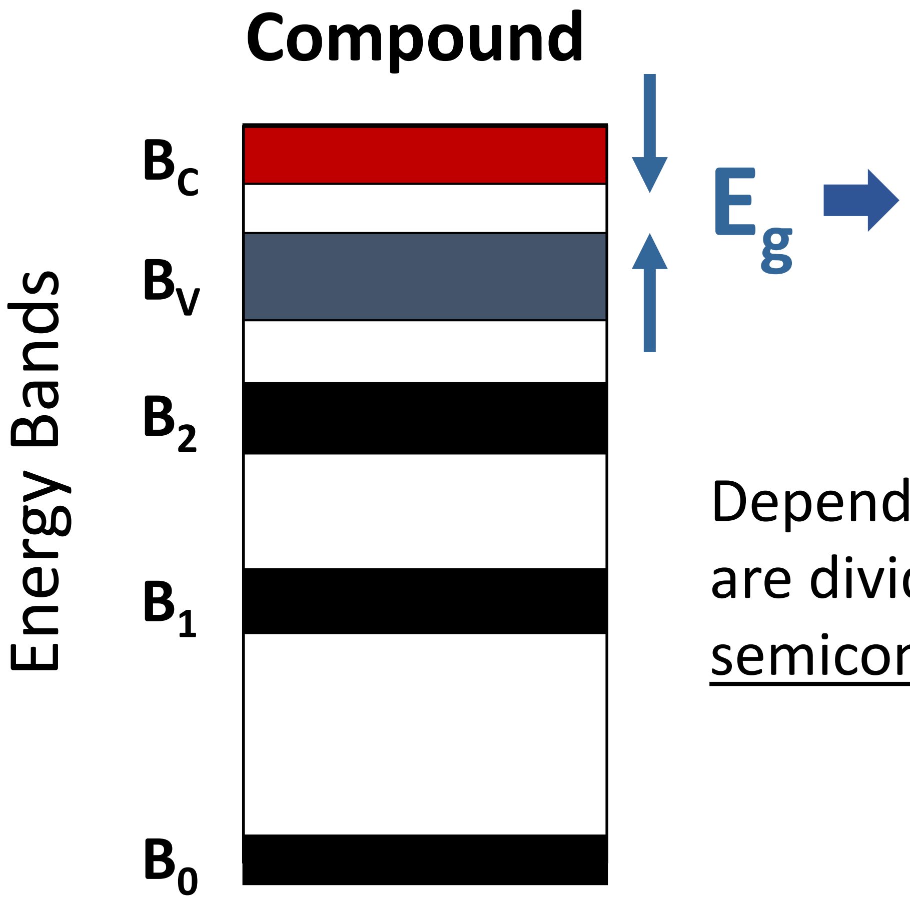


How LASERs work

Semiconductor Principles

SEMICONDUCTORS PRINCIPLES

1. The electrons are located inside energy bands being the last two called the Valence and the Conduction Bands, respectively, separated by an energy gap.

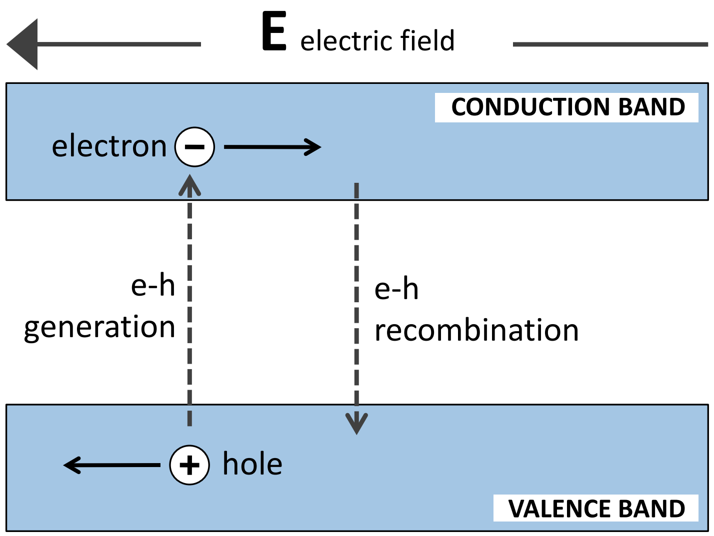


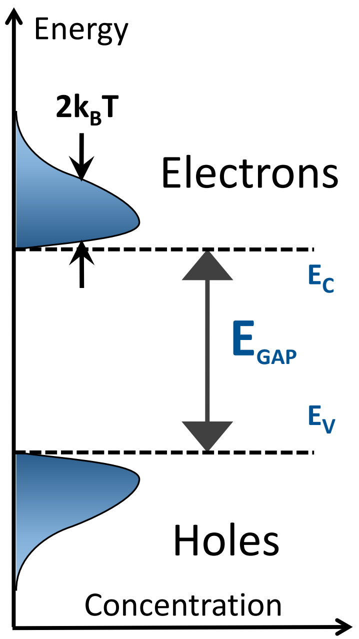
< 0.1 eV → Conductors
0.1-3 eV → Semiconductors
> 3 eV → Isolators

Depending on the energy gap, the materials are divided among: isolators, conductors and <u>semiconductors</u>.

[Intrinsic & Extrinsic Semiconductors]

Semiconductor Principles





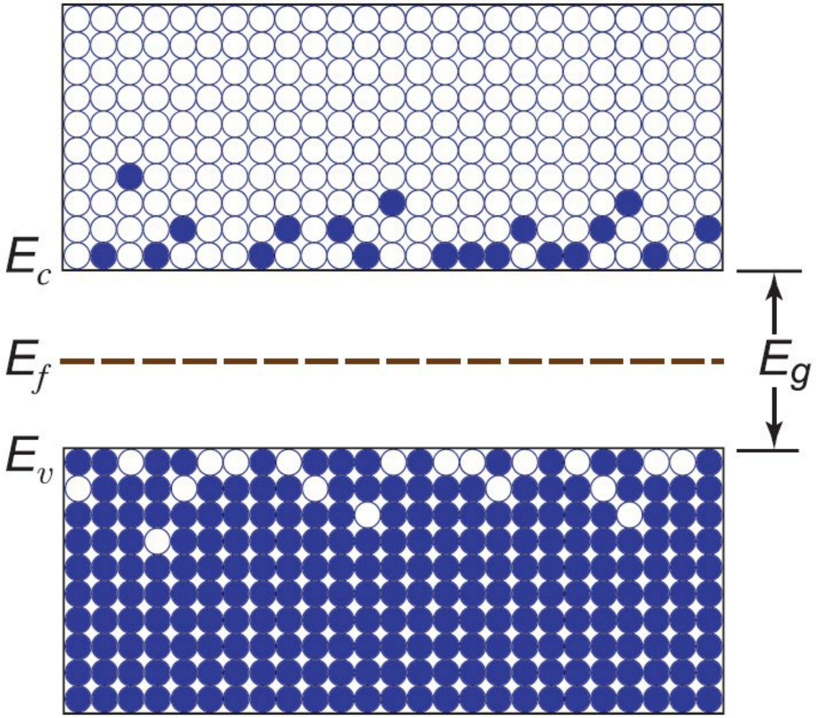
2. Electrons in the CB are not tied to any particular atom so they are free to move along the semiconductor.

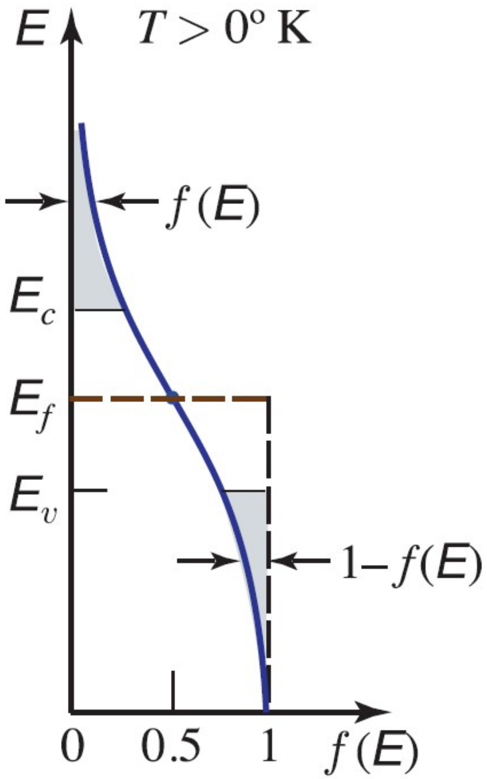
3. When an electron gets liberated from its atom and moves to CB leaves a **hole** in the VB which is called to have positive charge.

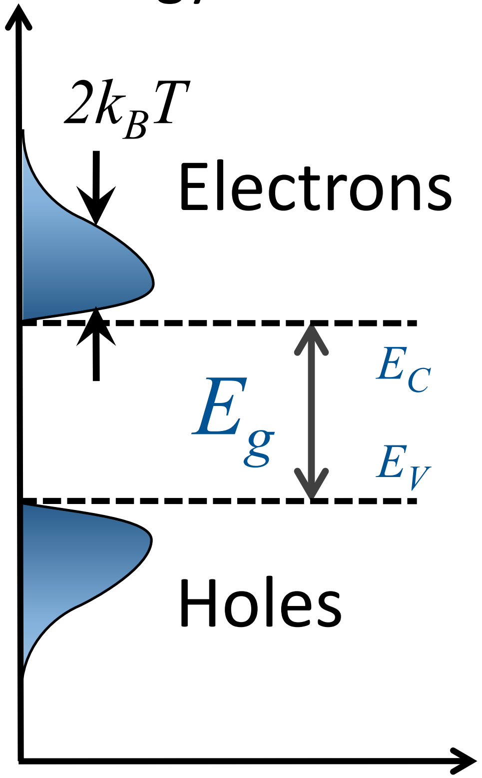
4. An electron placed in CB may return to VB occupying a hole an releasing its energy that can be in the form of a **photon**. This process is known as **electron-hole recombination**.

Semiconductor Principles

Carrier Concentration







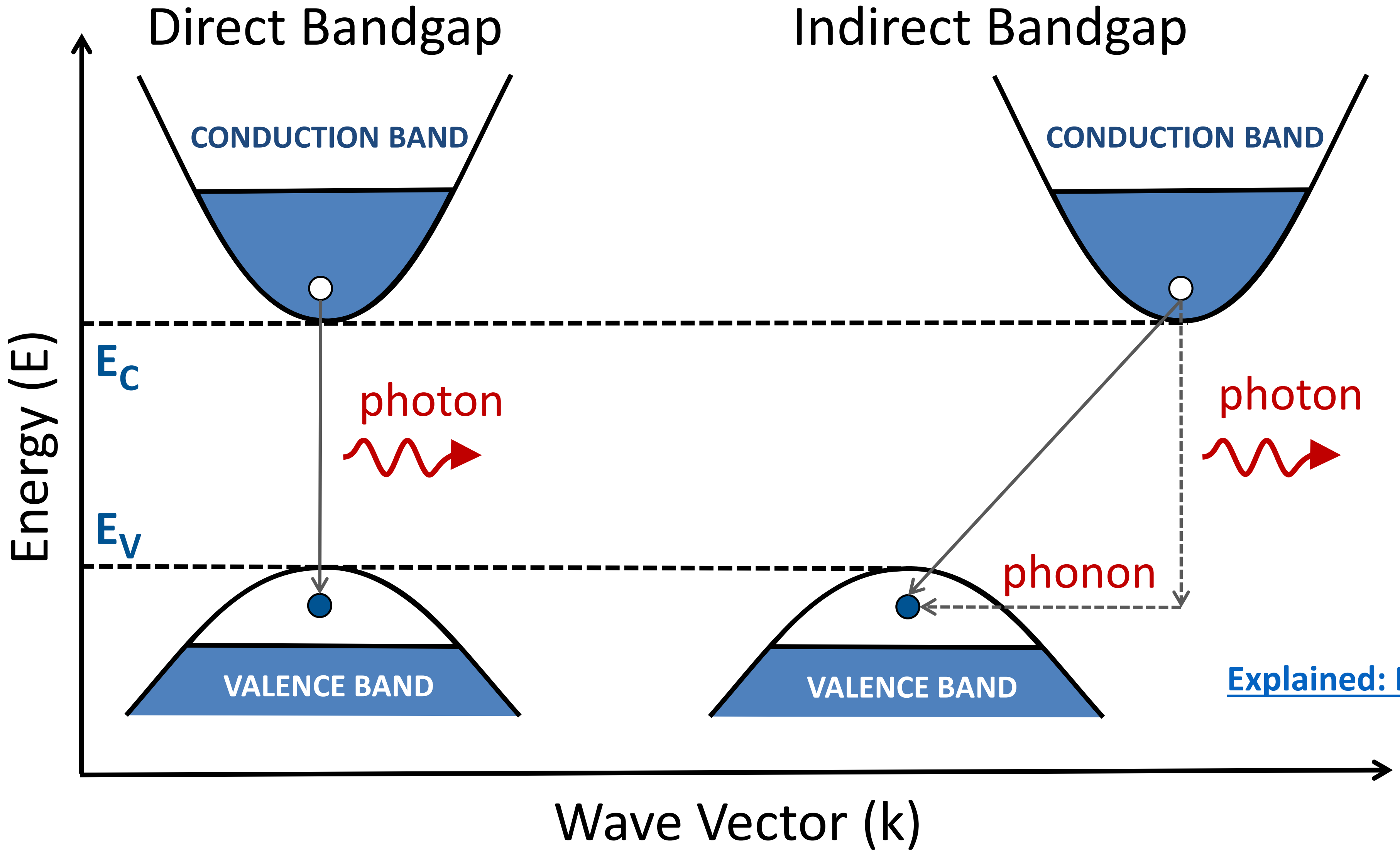
Fermi-Dirac Distribution

$$f(E) = \frac{1}{1 + e^{(E-E_f)/K_BT}}$$

E_f: Fermi Level

Semiconductor Principles

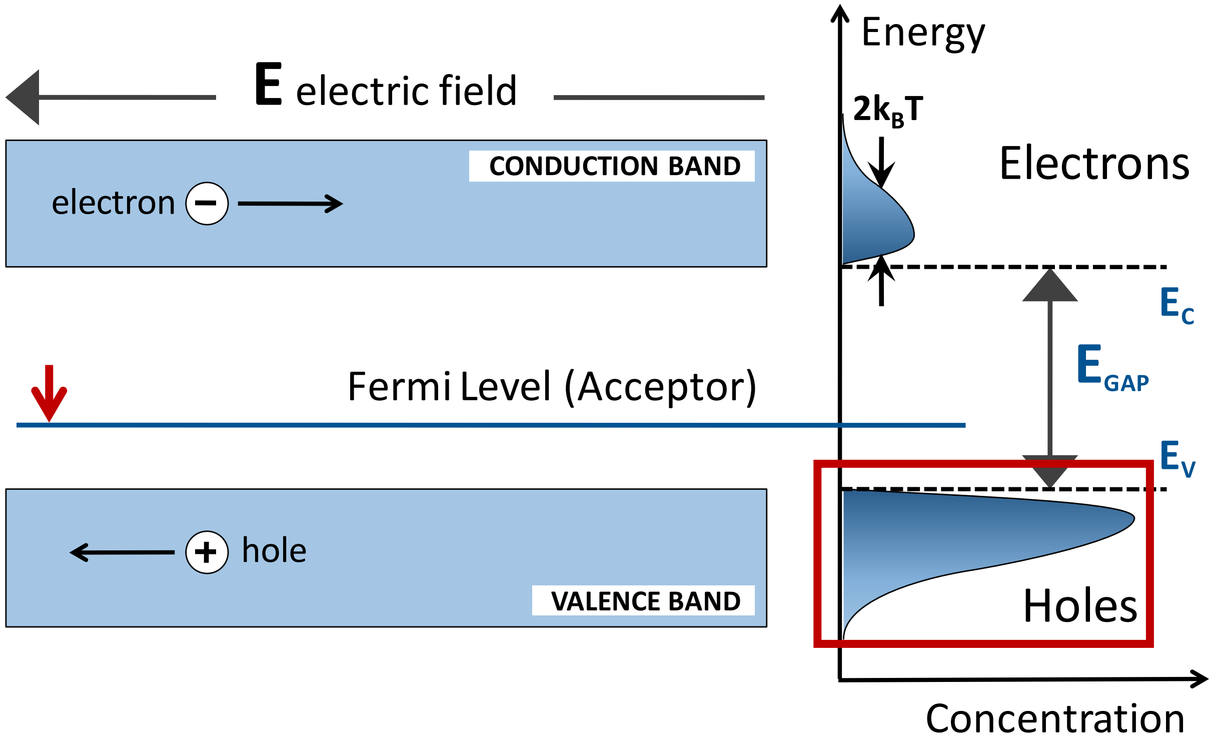
Energy-Momentum Relations



Explained: Phonons

P-type Semiconductor

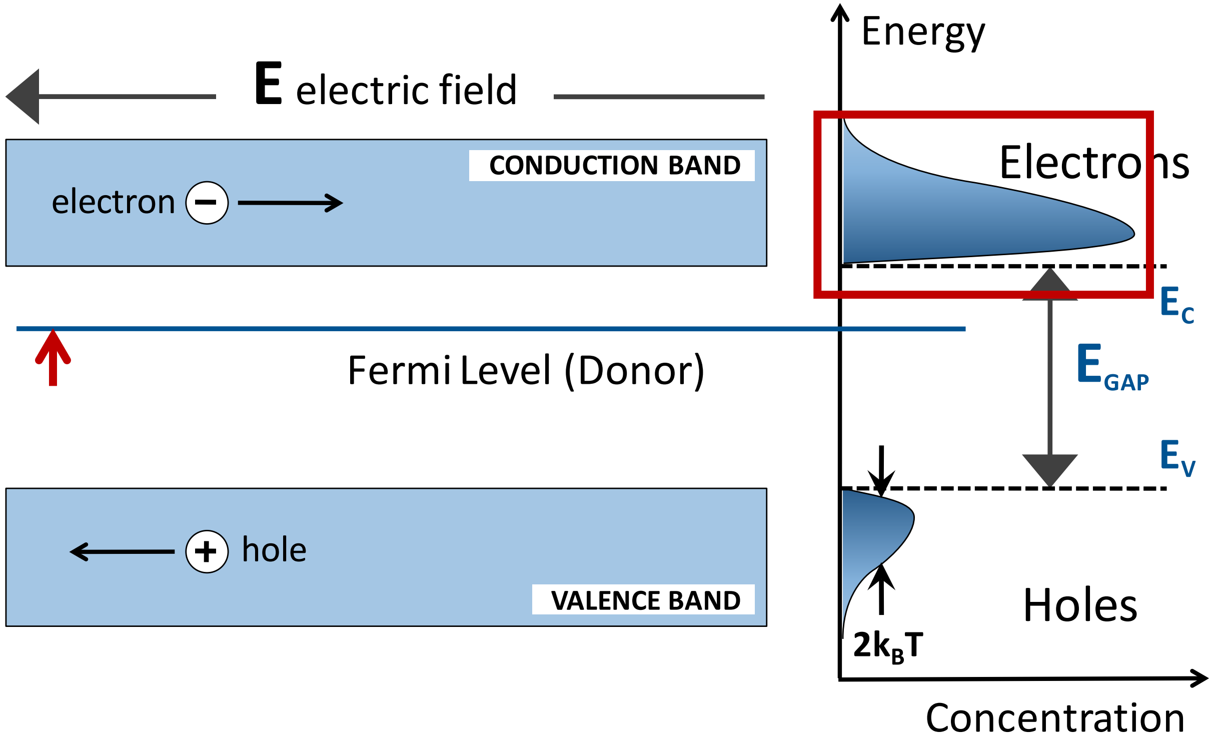
Some “acceptor” doping atoms are added which take electrons from the Conduction Band. A positive carrier flux is produced.



Semiconductor Principles

N-type Semiconductor

Some "donor" doping atoms are added which give electrons to the Conduction Band. A negative carrier flux is produced.

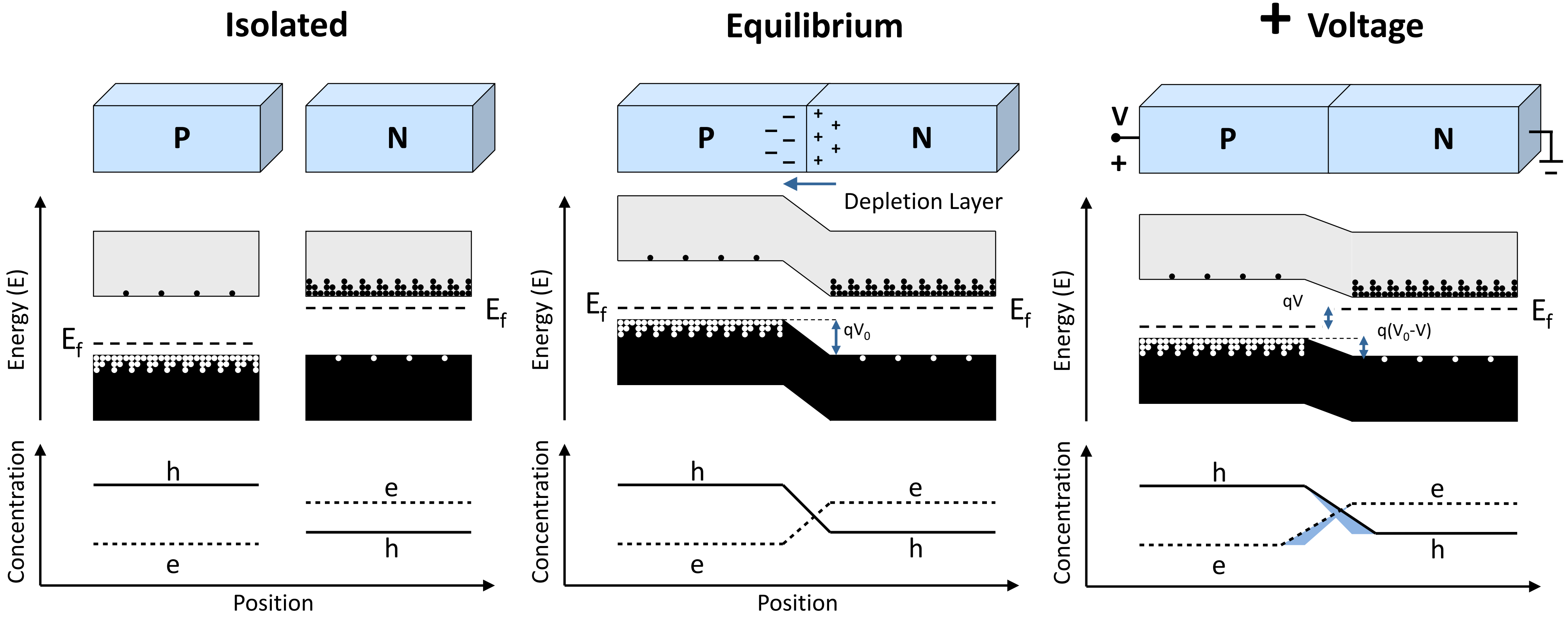


Semiconductor Principles

P-N Union

Homojunction

The P-N junction



In Thermal Equilibrium, the Fermi Level has to be continuous along the PN junction

Active Region 1-10 microns

$$\boxed{I = I_S\left[\exp\left(\frac{qV}{K_B T}\right) - 1\right]}$$

Diode

I_S : Saturation Current

The LED & Solar Cell

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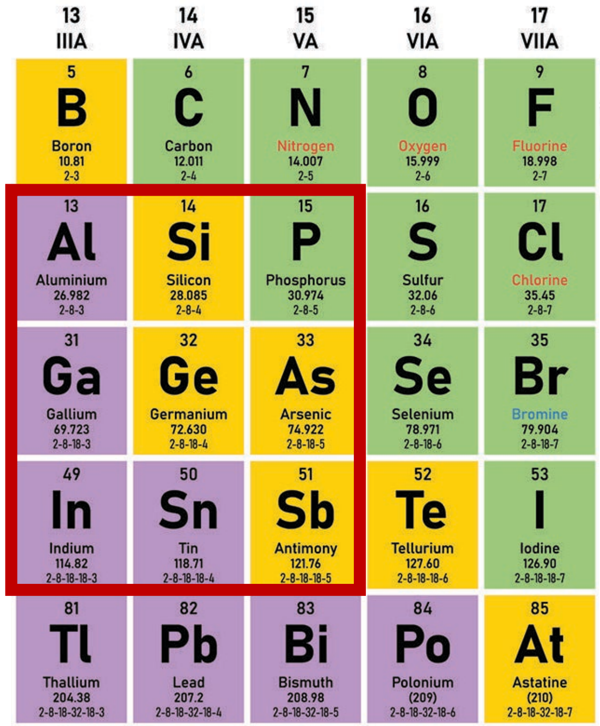
Semiconductor Principles

Semiconductors for Optical Sources



- Post-transition metals
- Metalloids
- Reactive nonmetals

$$E_g = h \cdot f_g = h \frac{c}{\lambda_g}$$

Material	E_g (eV)	λ_g (μm)	GAP
Ge	0.66	1.88	I
Si	1.11	1.15	I
AlP	2.45	0.52	I
AlAs	2.16	0.57	I
AlSb	1.58	0.75	I
GaP	2.26	0.55	I
GaAs	1.42	0.87	D
GaSb	0.73	1.70	D
InP	1.35	0.92	D
InAs	0.36	3.5	D
InSb	0.17	7.3	D

- ❑ Binaries → GaAs (1st window)
- ❑ Ternaries → $Al_xGa_{1-x}As$ (1st window)
  → $In_xGa_{1-x}As$ (2nd & 3rd window)
- ❑ Quaternaries → $In_xGa_{1-x}As_yP_{1-y}$ (1st ,2nd & 3rd window)

Quantum Efficiency

QUANTUM EFFICIENCY

$$\eta \equiv \frac{\langle N^o phot/seg \rangle}{\langle N^o e-h/seg \rangle} = \frac{P_{OUT}/hf}{I/q}$$

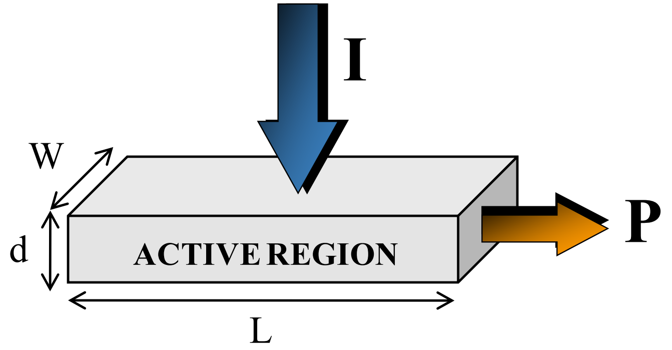
$$\boxed{P_{OUT} = \eta \frac{hf}{q} I}$$ [W]

0.8

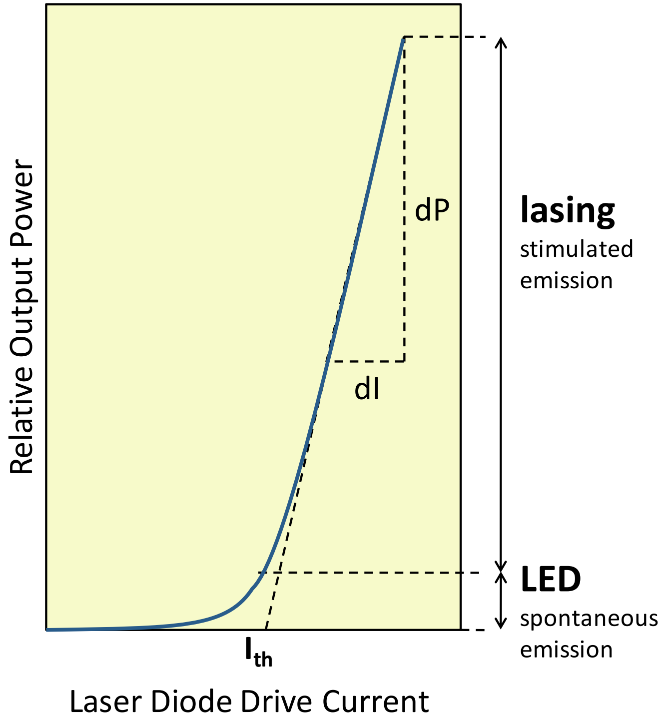
LED → $\eta \sim 6\%$

LASER → $\eta \sim 70\%$

q: electron charge ($1{,}6 \cdot 10^{-19}$ C)



light-current characteristic



Quantum Efficiency

Internal / External Quantum Efficiency

$$\eta \equiv \frac{\left\langle N^{o}\mathrm{phot}/\mathrm{seg}\right\rangle_{out}}{\left\langle N^{o}e-h/\mathrm{seg}\right\rangle_{total}} = \underbrace{\frac{\left\langle N^{o}\mathrm{phot}/\mathrm{seg}\right\rangle_{out}}{\left\langle N^{o}\mathrm{phot}/\mathrm{seg}\right\rangle_{generated}}}_{\eta_e} \times \underbrace{\frac{\left\langle N^{o}\mathrm{phot}/\mathrm{seg}\right\rangle_{generated}}{\left\langle N^{o}e-h/\mathrm{seg}\right\rangle_{total}}}_{\eta_i}$$

$$\boxed{\eta \equiv \eta_i \cdot \eta_e}$$

Si → $\eta_i \sim 10^{-5}$

AsGa → $\eta_i \sim 0.7$

Inefficiency Causes

- Non-radiative recombinations → thermal energy
- Phonon → kinetic energy

} **INTERNAL**

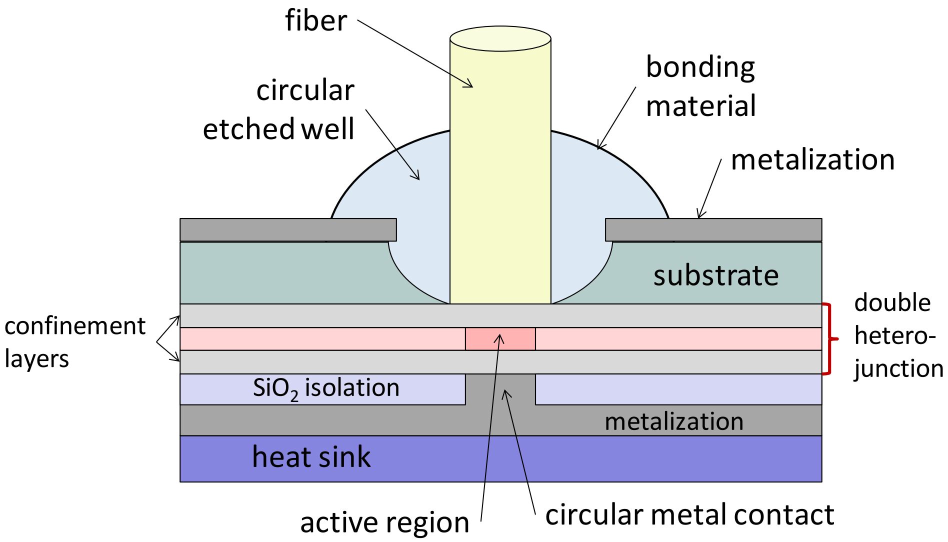
- Stimulated absorption and scattering in the active region
- Emitted light omnidirectionality
- Reflection in the source-air transition

} **EXTERNAL**

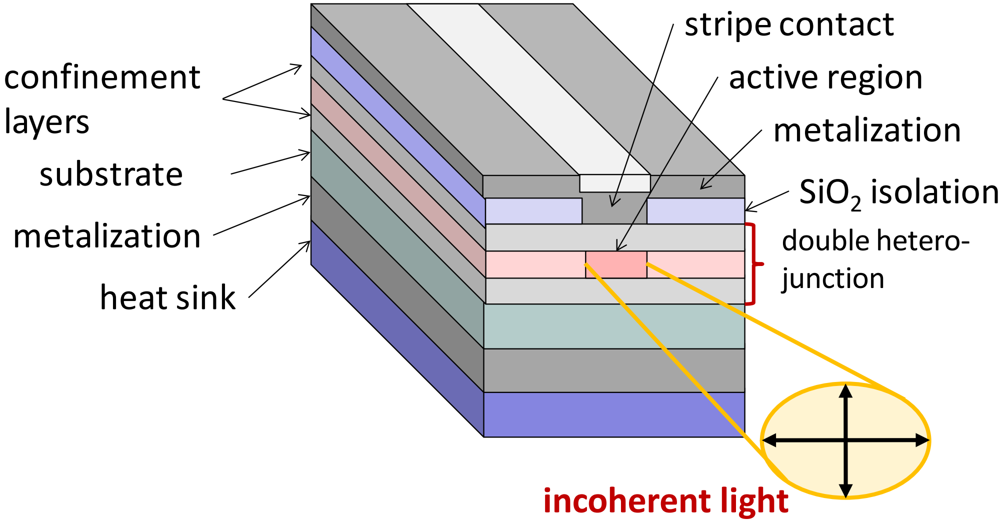
LIGHT-EMITTING DIODE (LED)

LED
(Light Emitting Diode)

Surface-Emitting LED

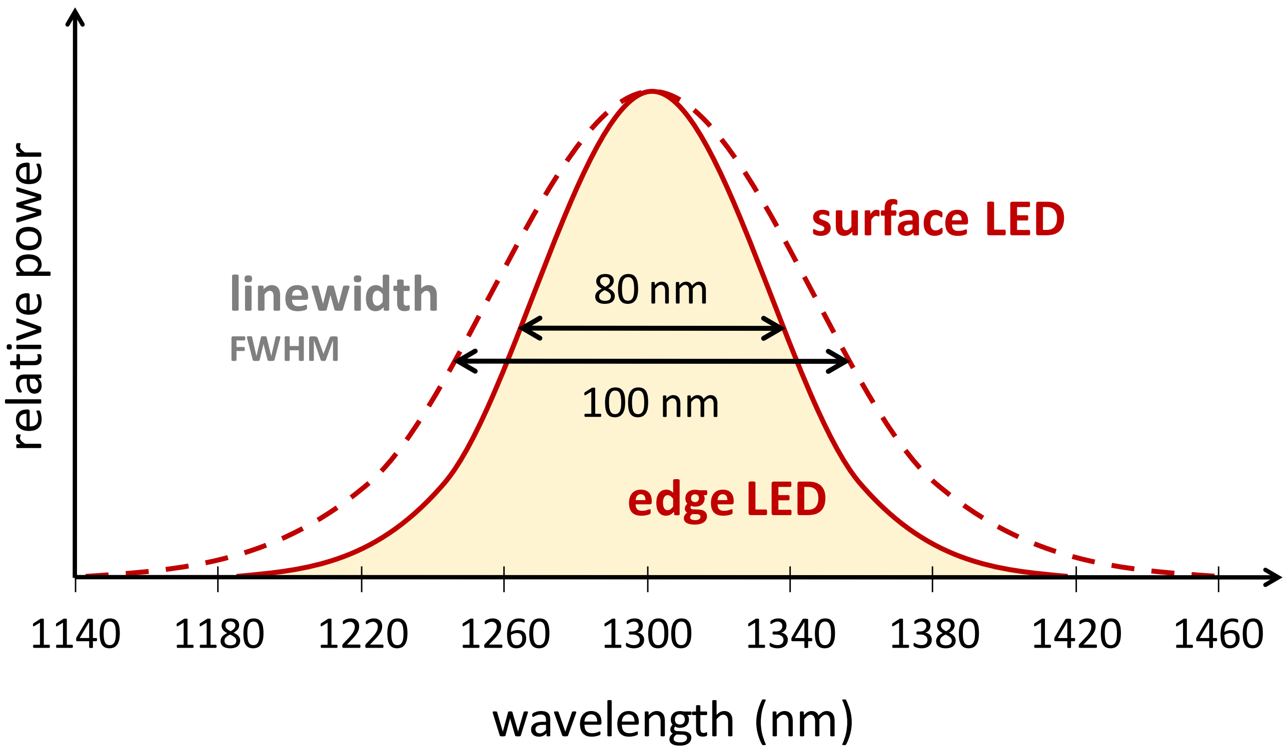


Edge-Emitting LED



Characteristics Overview

LED characteristic figures

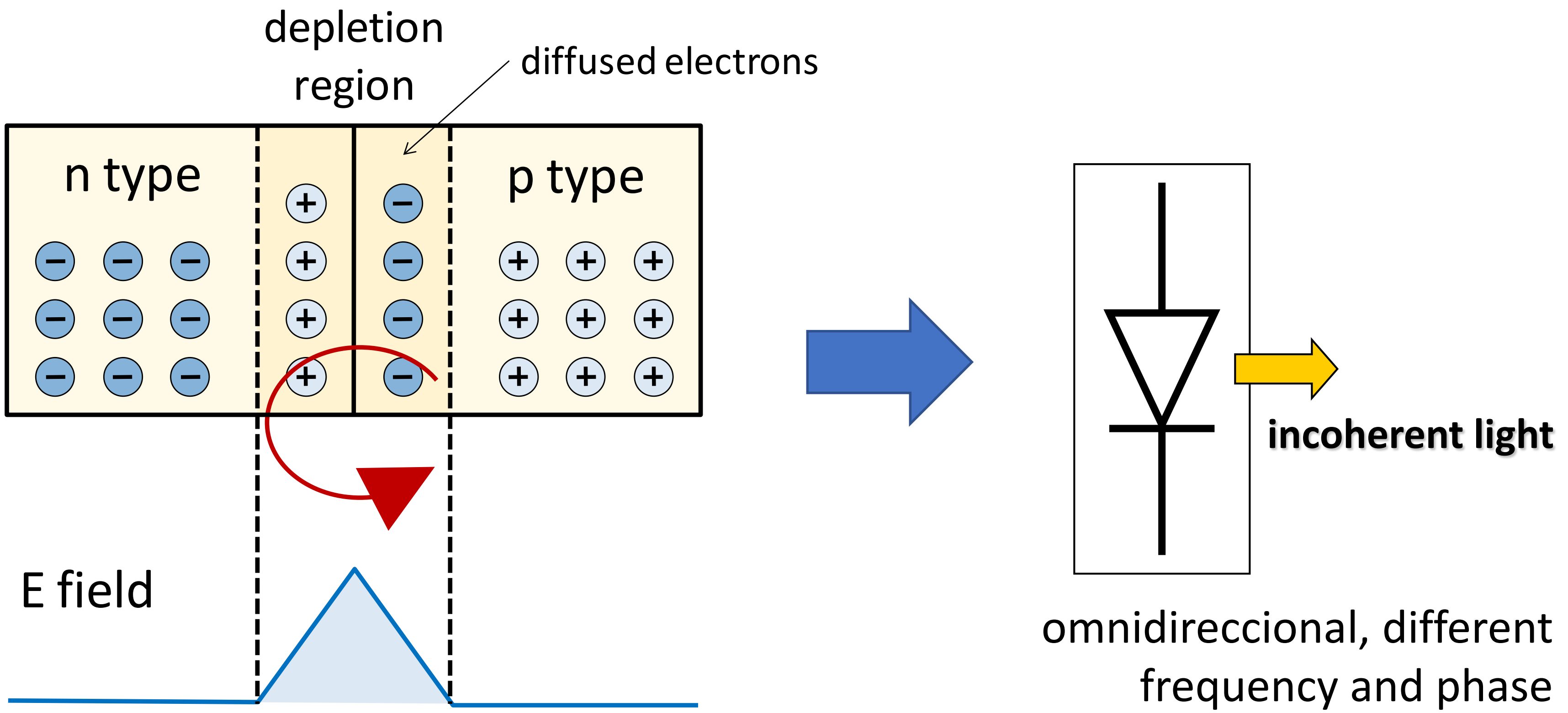


- BW up to 100 MHz → R_B up to 100 Mb/s
- $\Delta\lambda$ huge → 100 nm
- P_{OUT} very small → -20 dBm

Working Principle

WORKING PRINCIPLE

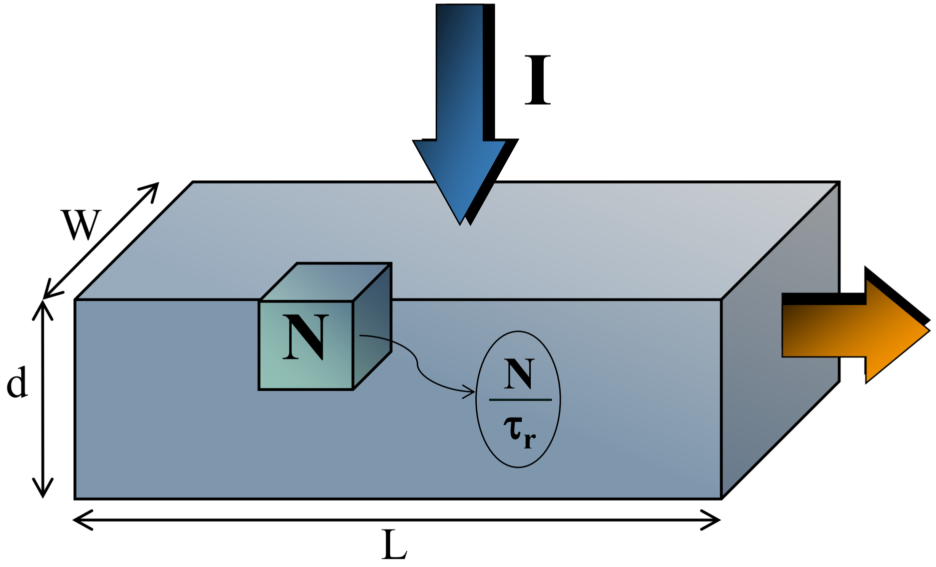
"LED source is a diode (PN junction) directly polarized which emits light by **spontaneous emission** (incoherent light) thanks to an electron-hole recombination process"



omnidireccional, different frequency and phase

Working Principle

Carrier Injection – Optical Power



quantum efficiency

$$\eta \equiv \frac{\langle N^o fot/seg \rangle}{\langle N^o e-h/seg \rangle} = \frac{P_{OUT}/hf}{I/q}$$

$$\boxed{P = \eta \frac{N}{\tau_r} V \cdot hf \equiv \frac{Joules}{s}}$$

$$\frac{N}{\tau_r} \equiv \frac{recomb/m^3}{s} \Longrightarrow \frac{N}{\tau_r} V \equiv \frac{recomb}{s} \Longrightarrow \eta \frac{N}{\tau_r} V \equiv \frac{fotons}{s}$$

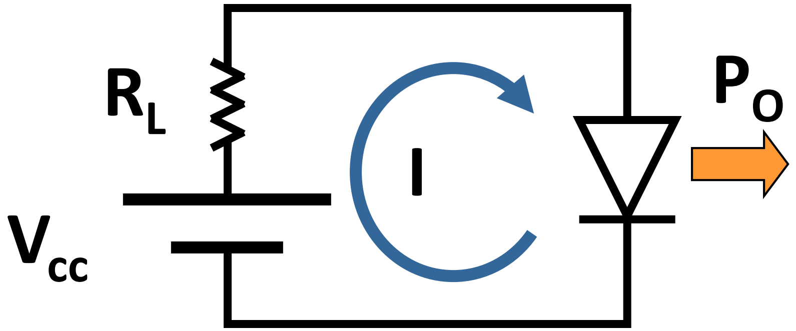
$$P_{OUT} = \eta \frac{hf}{q} I = \eta \frac{N}{\tau_r} V \cdot hf \Longrightarrow \boxed{\frac{N}{\tau_r} = \frac{I}{qV}}$$

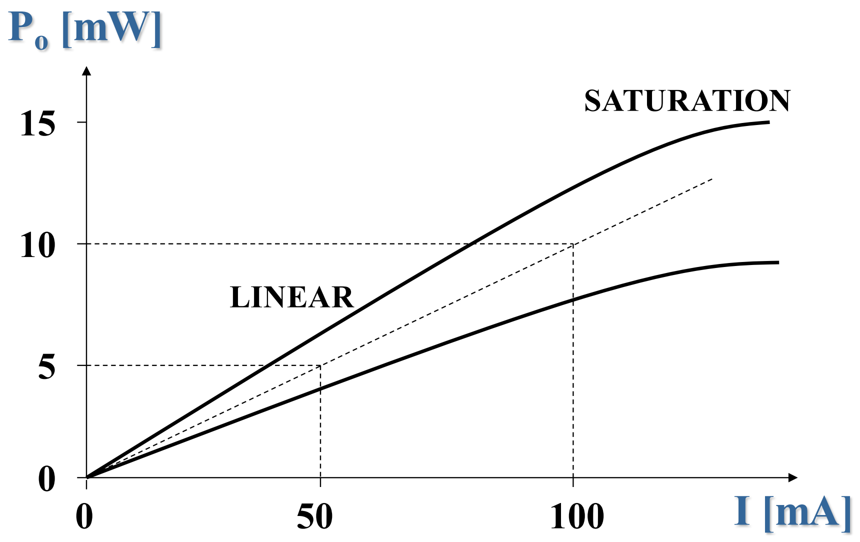
equilibrium state

Working Principle

Light – Current characteristic

"Representation of the optical power emitted by the source as a function of the polarization electrical current intensity"





$$\boxed{P_{OUT} = \eta \frac{hf}{q} I}$$ [W]

typical efficiency : $0.1\ \mu W/mA$

AsGa → $\eta_i \sim 0.7$ $\quad \dfrac{hf}{q} \approx 0.8$

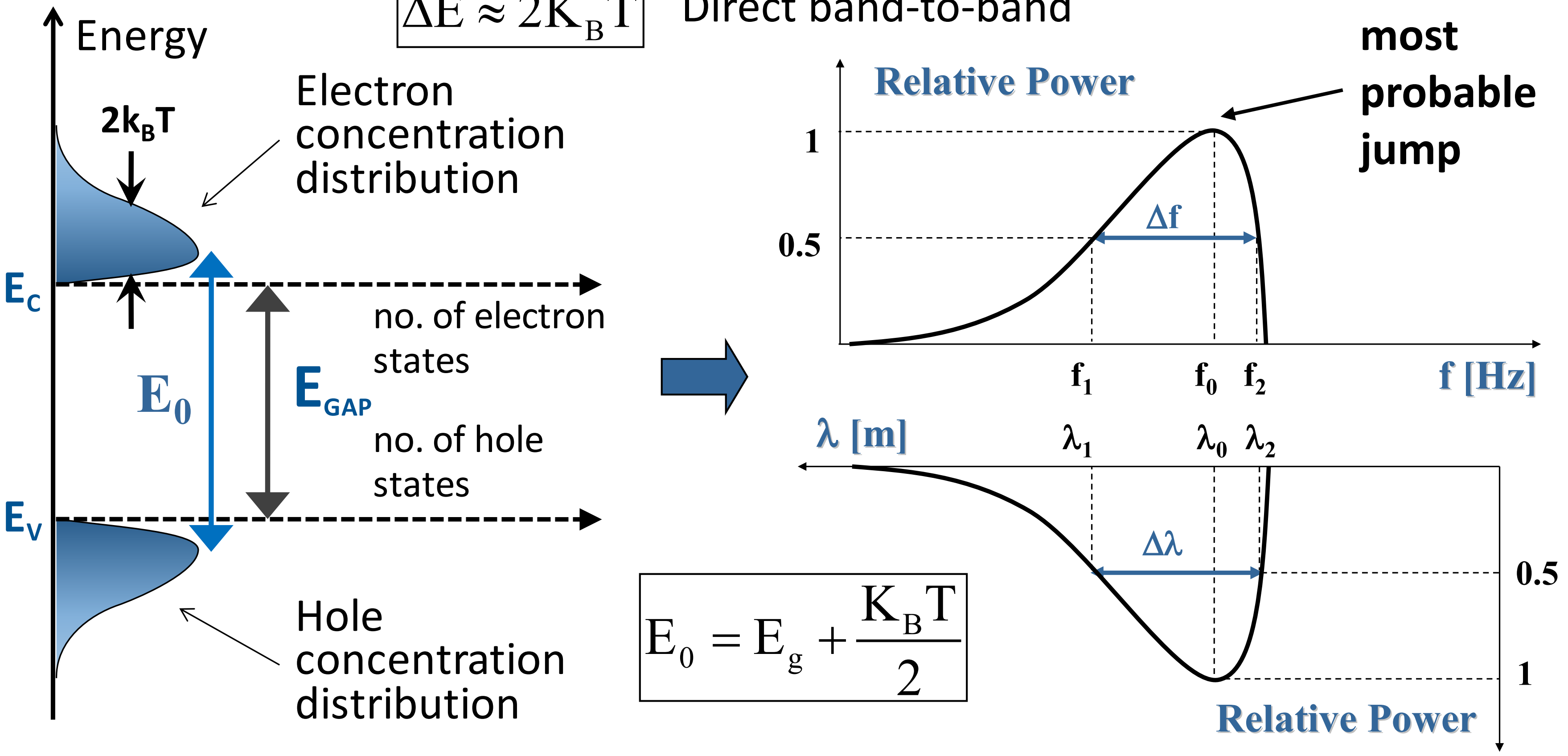
Working Principle

Power Spectral Density

"One of the main characteristics of LED diodes is its spectral width due to the fact that the light is incoherent (spontaneous emission)"

$$\boxed{\Delta E \approx 2K_BT}$$

Direct band-to-band



$$\boxed{E_0 = E_g + \frac{K_BT}{2}}$$

Working Principle

Peak wavelength - λ_0 (most probable jump):

$$E_0 = E_g + \underbrace{\frac{K_B T}{2}}_{\text{thermal}} = hf_0 = h\frac{c}{\lambda_0} \Rightarrow \boxed{\lambda_0 = \frac{hc}{E_g + K_B T/2}} \approx \frac{hc}{E_g}$$

[J]

Spectral width - $\Delta\lambda$:

$$\Delta\lambda \equiv \lambda_2 - \lambda_1 = \frac{c}{f_2} - \frac{c}{f_1} = \frac{hc}{E_2} - \frac{hc}{E_1} = hc\left[\frac{E_1 - E_2}{E_1 E_2}\right]$$

$$\Delta E << E_0$$

$$E_c \approx E_0$$

$$= hc\frac{\Delta E}{\left(E_c - \frac{\Delta E}{2}\right)\left(E_c + \frac{\Delta E}{2}\right)} = hc\frac{\Delta E}{E_c^2 - \left(\frac{\Delta E}{2}\right)^2} \approx hc\frac{\Delta E}{E_0^2}$$

$$\approx hc\frac{2K_B T}{E_g^2} \approx \boxed{\frac{2K_B T}{hc}\lambda_0^2}$$

$$\Delta E \approx 2K_B T \qquad E_0 = E_g + \frac{K_B T}{2} \approx E_g$$

Working Principle

$$\Delta\lambda \approx \frac{2K_BT}{hc}\lambda_0^2 = \underbrace{\frac{2K_BT}{hc}\lambda_0}_{0.03-0.06}\lambda_0 \Rightarrow \Delta\lambda \rightarrow$$ 30 – 100 nm

ΔE_{LED}~ 3-4 K_BT/q

Temperature Effect :

$$E_0 = E_g(T) + \frac{K_BT}{2} \rightarrow \lambda_0(T)$$

$$\Delta\lambda(T) \approx \frac{2K_BT}{hc}\lambda_0^2(T)$$

$\Delta\lambda_{LED}$~ 0.3-0.4 nm/ºC

Incoherent Light :

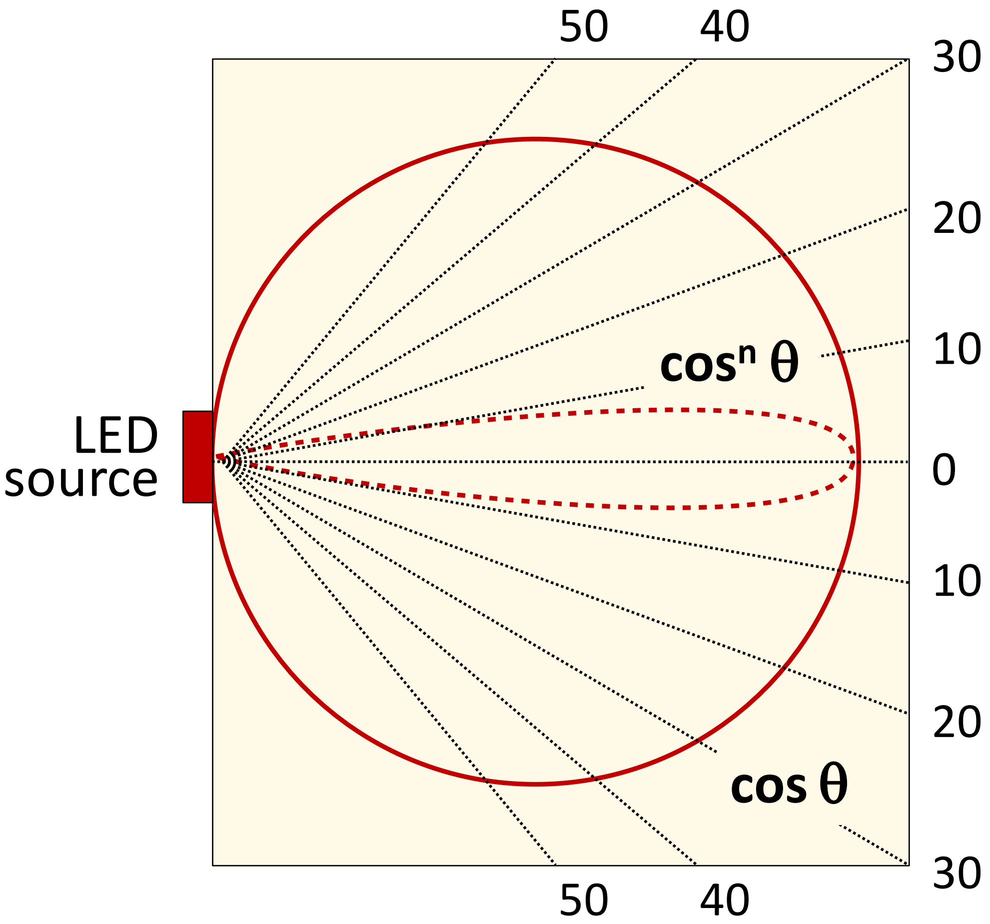
spontaneous emission → photons with random frequency, phase, and direction (incoherent light)

Bose-Einstein statistics $$\sigma_m^2 = \langle m\rangle\left(\langle m\rangle + 1\right)$$

Light Coupling

LED LOSSES

Radiation Diagram



Lambert's Law

$$I(\theta) = I_0 \cos\theta$$

$$P(\theta) = P_0 \cos\theta$$

$$P_T = 2\pi \int_0^{\pi/2} P(\theta) \sin\theta \, \partial\theta$$

$$P_i = 2\pi \int_0^{\theta_a} P(\theta) \sin\theta \, \partial\theta$$

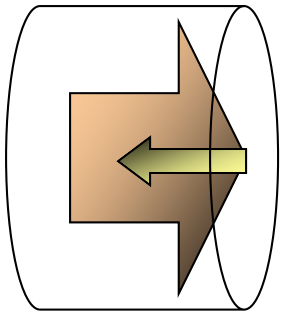
$$\boxed{\eta_c \equiv \frac{P_i}{P_T} = \sin^2\theta_a = \left[\frac{NA}{n_0}\right]^2}$$

Light Coupling

Refractive Indices Mismatch (reflection)

$$P_{IN} = 2\pi \int_0^{\theta_a} (1-R) P(\theta) \sin\theta \cdot \partial\theta$$

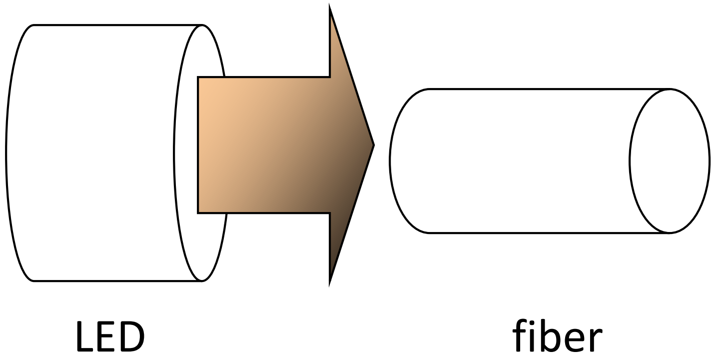
$$R = \left(\frac{n_{ZA} - n_0}{n_{ZA} + n_0} \right)^2 \longleftarrow$$ Fresnel's Law



LED/fiber Effective Area Mismatch

$$P_{IN} = 2\pi \int_0^{\theta_a} L P(\theta) \sin\theta \cdot \partial\theta$$

$$L = \left(\frac{\phi_{fibra}}{\phi_{LED}} \right)^2 \longleftarrow \varphi_{LED} > \varphi_{fiber}$$



LED Dynamics

LED DYNAMICS

"The way the carrier equilibrium is restored after a current fluctuation can be modeled by what is known as LED's **rate equation**"

$$\left\{ \begin{array}{c} \text{carrier} \\ \text{density} \\ \text{variation} \end{array} \right\} = \left\{ \begin{array}{c} \text{carrier} \\ \text{density} \\ \text{generation} \\ \text{rate} \end{array} \right\} - \left\{ \begin{array}{c} \text{carrier density} \\ \text{recombination} \\ \text{rate} \end{array} \right\}$$

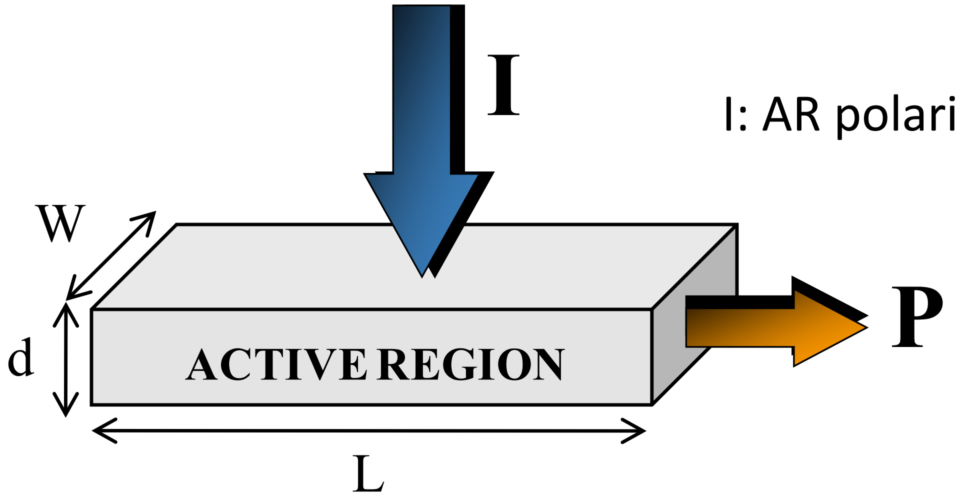
$$\frac{\partial N}{\partial t} \qquad\qquad I \qquad\qquad N, \tau_r$$

I: electrical current

τ_r: carrier lifetime

N: AR carrier density

LED Dynamics



I: AR polarization current

current density $J \equiv \dfrac{I}{\text{àrea}} = \dfrac{I}{WL}$

carrier generation $\equiv \dfrac{I}{q \cdot V} = \dfrac{J}{q \cdot d}$

carrier recombination $\equiv \dfrac{N}{\tau_r}$

LED's rate equation

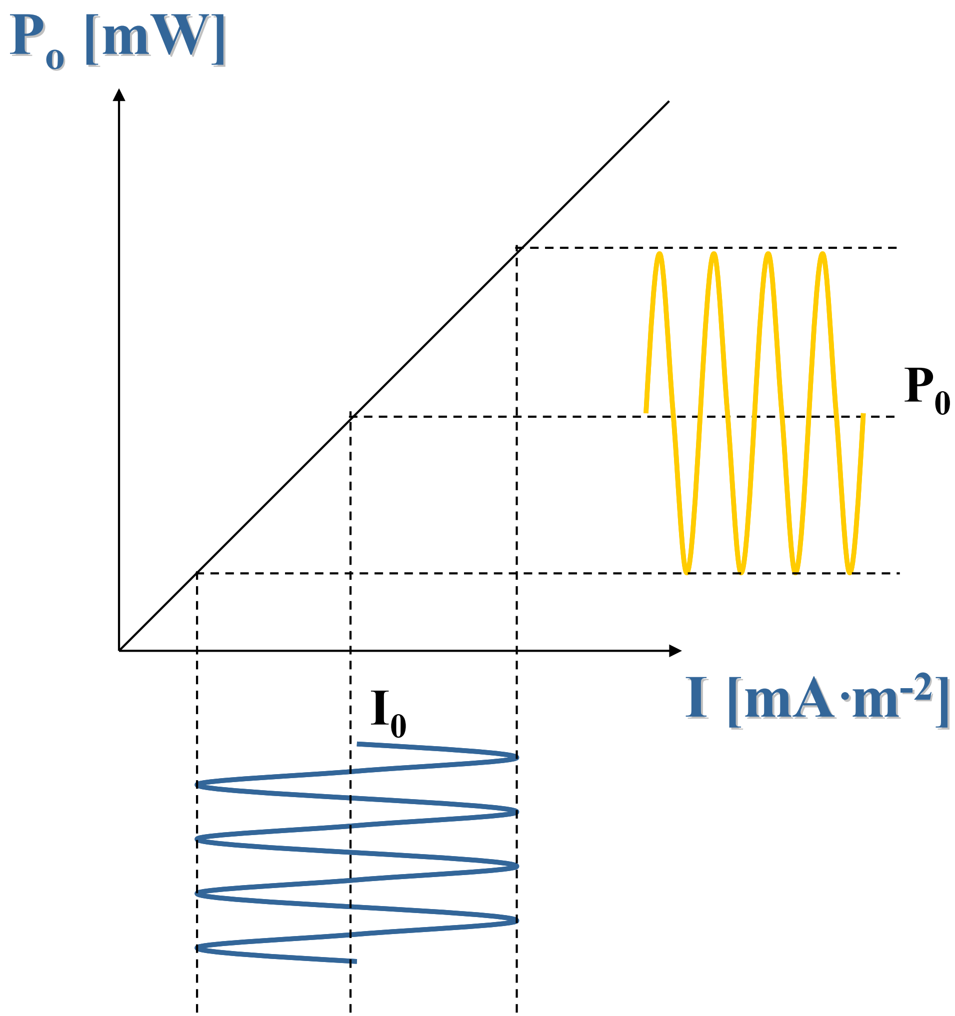
$$\boxed{\frac{\partial N}{\partial t} = \frac{I}{qV} - \frac{N}{\tau_r}} \quad [m^{-3}s^{-1}]$$

Unstimulated state $t_0 \begin{cases} N = N_0 \\ I = 0 \end{cases}$

$$\frac{\partial N}{\partial t} = -\frac{N}{\tau_r} \rightarrow N = N_0 e^{-t/\tau_r} \xrightarrow{t \to \infty} 0$$

LED
Direct Modulation

LED's modulation - sinusoidal modulation



sinusoidal stimulus

$$I(t) \equiv I_0\left[1 + m_I e^{j(\omega_0 t+\phi)}\right]$$

$$N(t) \equiv N_0\left[1 + m_N e^{j(\omega_0 t+\phi-\theta_N)}\right]$$

$$P(t) \equiv P_0\left[1 + m_N e^{j(\omega_0 t+\phi-\theta_N)}\right]$$

I_0: DC electrical component

Optical Power

$$\boxed{P(t) = \eta \frac{N(t)}{\tau_r} V \cdot hf}$$

LED Direct Modulation

Modulation Signal

$$\boxed{I(t)=I_0\left[1+m_I e^{(j\omega_0 t+\phi)}u(t)\right]}$$

$$N(t)=\underbrace{\frac{I_0\tau_r}{qV}}_{N_0}\left\{\left[1-e^{-t/\tau_r}\right]+\underbrace{\frac{m_I}{1+j\omega_0\tau_r}}_{m_N}e^{j\phi}\left[e^{j\omega_0 t}-e^{-t/\tau_r}\right]u(t)\right\}$$

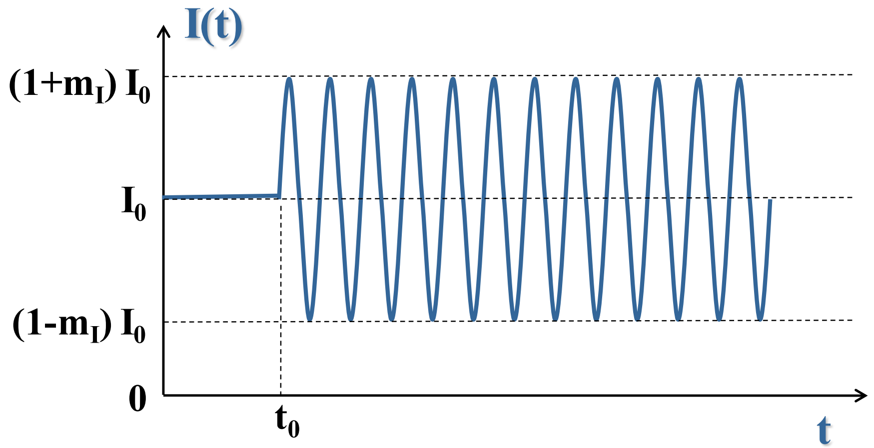
$$P(t)=\eta\frac{N(t)}{\tau_r}V\cdot hf$$

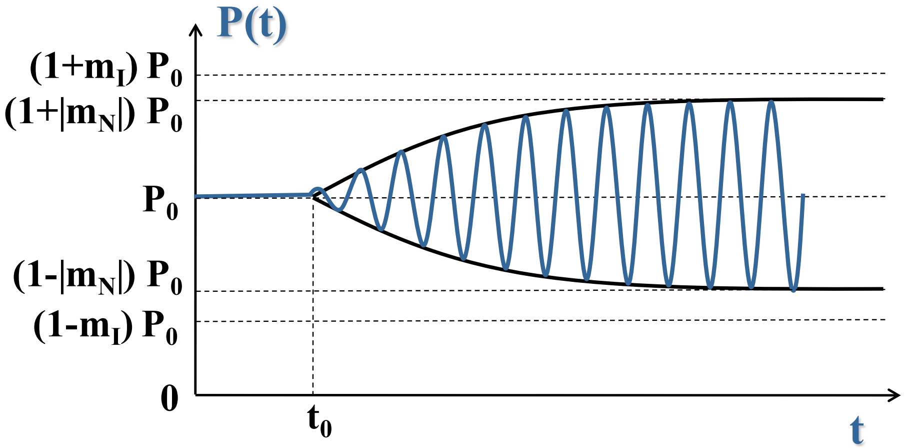
$$\boxed{P(t)=\underbrace{\eta\frac{hf}{q}I_0}_{P_0}\left\{\left[1-e^{-t/\tau_r}\right]+\underbrace{\frac{m_I}{1+j\omega_0\tau_r}}_{m_N}e^{j\phi}\left[e^{j\omega_0 t}-e^{-t/\tau_r}\right]u(t)\right\}}\xrightarrow{t\to\infty}P_0\left\{1+m_N e^{(j\omega_0 t+\phi)}\right\}$$

modulation index

$$\left|m_N\right|=\frac{m_I}{\sqrt{1+\left(\tau_r\omega_0\right)^2}}$$

$$\theta_N=tg^{-1}\left\{-\tau_r\omega_0\right\}$$





LED Direct Modulation

LED's Transfer Function

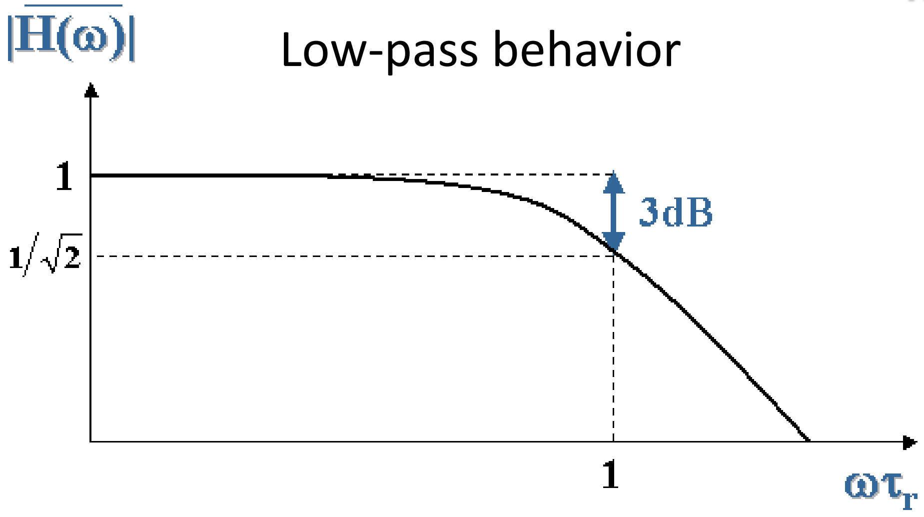
$$H(\omega_0) \equiv \frac{\Delta P}{\Delta I}$$

$$P(t) = P_0\left[1 + \frac{m_I}{1 + j\omega_0\tau_r} e^{j\omega_0 t}\right] \rightarrow \Delta P = P_0 \frac{m_I}{1 + j\omega_0\tau_r} e^{j\omega_0 t}$$

$$I(t) = I_0\left[1 + m_I e^{j\omega_0 t}\right] \rightarrow \Delta I = I_0 m_I e^{j\omega_0 t}$$

$$P_0 = \eta \frac{I_0}{q} hf$$

$$\boxed{H(\omega_0) = \eta \frac{hf}{q} \frac{1}{1 + j\omega_0\tau_r}}$$



Low-pass behavior

modulation cutoff frequency

$$|H(\omega_0)| = \eta \frac{hf}{q} \frac{1}{\sqrt{1 + (\omega_0\tau_r)^2}}$$

$$\omega_0 = \frac{1}{\tau_r} \rightarrow \boxed{f_{3dB} = \frac{1}{2\pi\tau_r}}$$

typically: 10–100 MHz

LED Direct Modulation

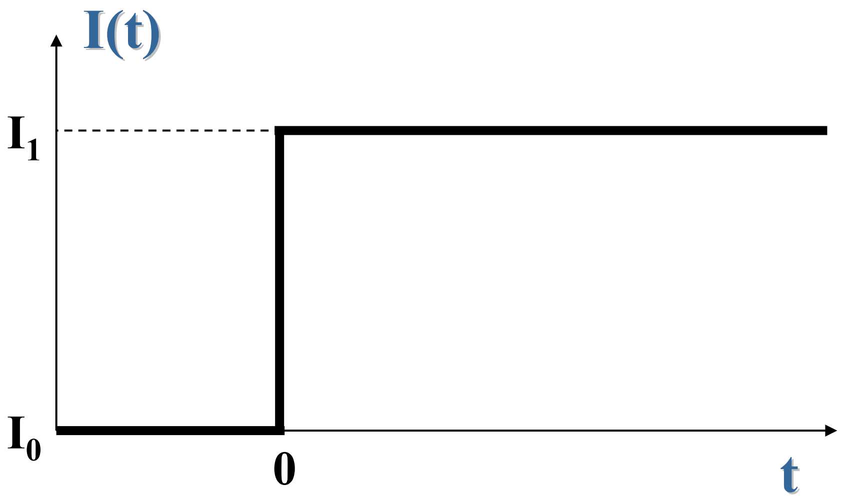
Digital Modulation

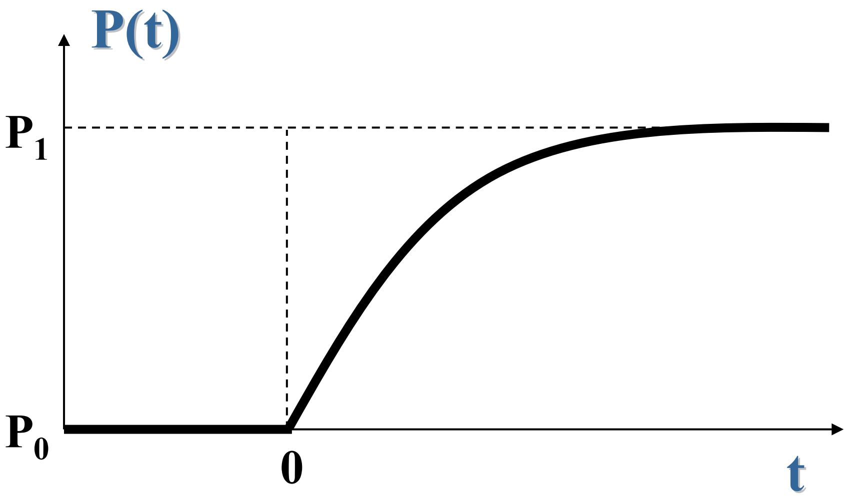
graó de corrent

$$I(t) \equiv I_0 + \left[I_1 - I_0\right] \cdot u(t)$$

$$N(t) = \underbrace{\frac{I_0}{qV}\tau_r}_{N_0} + \underbrace{\frac{I_1 - I_0}{qV}\tau_r}_{N_1 - N_0}\left(1 - e^{-t/\tau_r}\right) \cdot u(t)$$

$$P(t) = \underbrace{\eta \frac{I_0}{q} hf}_{P_0} + \underbrace{\eta \frac{I_1 - I_0}{q} hf}_{P_1 - P_0}\left(1 - e^{-t/\tau_r}\right) \cdot u(t)$$





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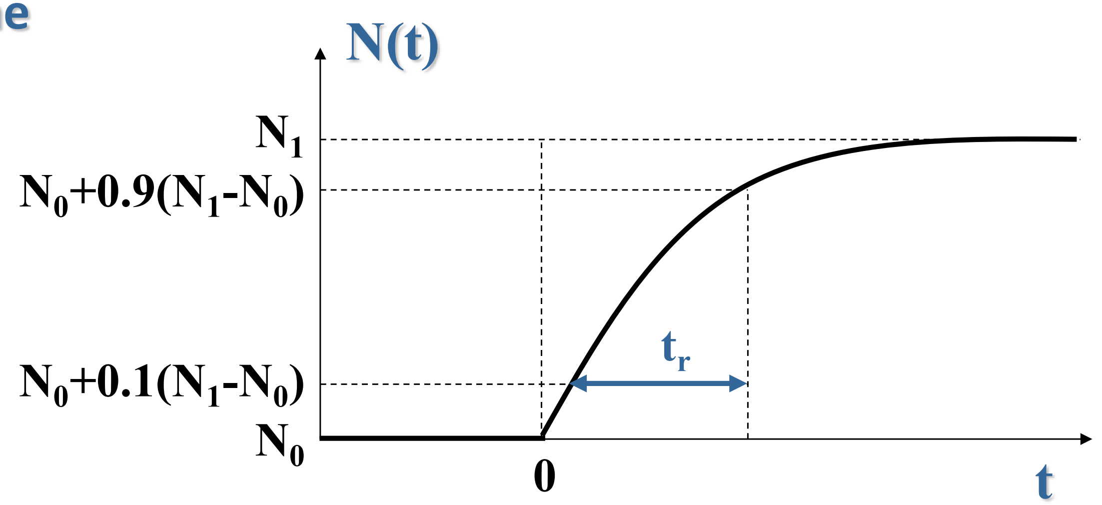
LED Direct Modulation

Response Time



$$N(t) = N_0 + (N_1 - N_0)\left(1 - e^{-t/\tau_r}\right)$$

$$N_f - N_0 = (N_1 - N_0)\left(1 - e^{-t_f/\tau_r}\right)$$

$$e^{-t_f/\tau_r} = 1 - \frac{N_f - N_0}{N_1 - N_0} = \frac{N_1 - N_f}{N_1 - N_0}$$

$$t_f = \tau_r \ln\left(\frac{N_1 - N_0}{N_1 - N_f}\right) = \tau_r \ln\left(\frac{P_1 - P_0}{P_1 - P_f}\right)$$

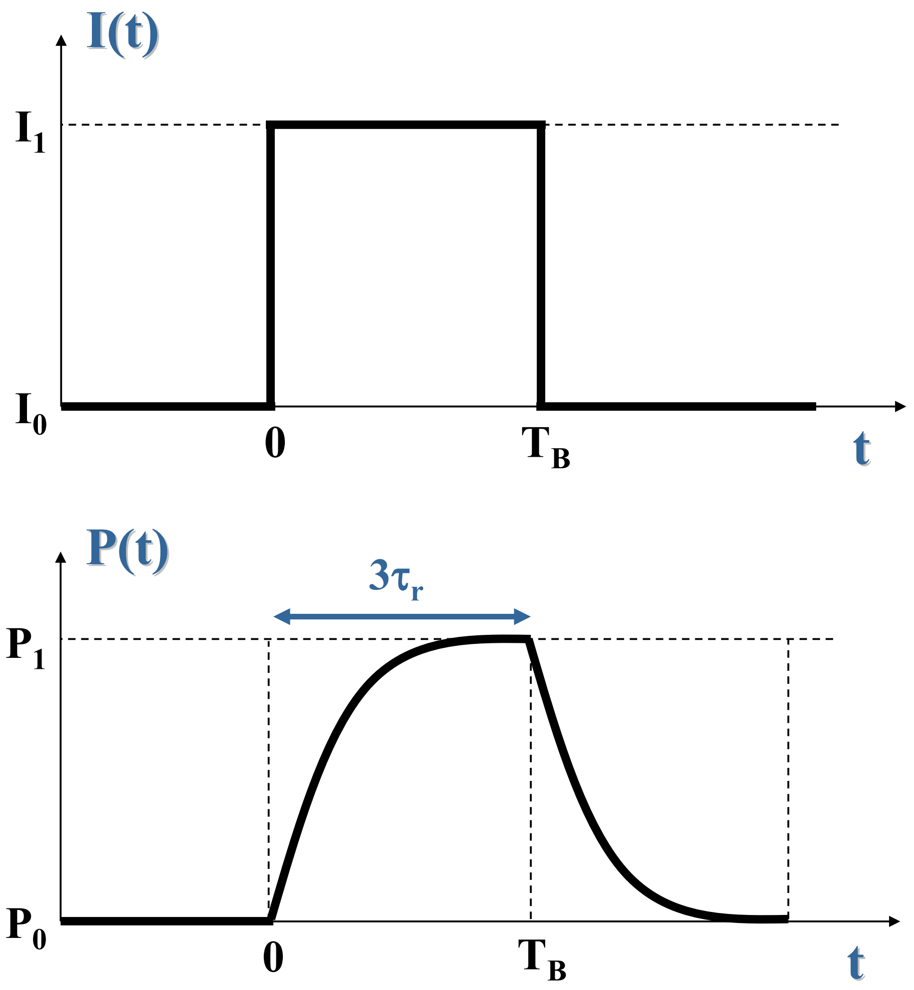
$$t_{0.1} = \tau_r \ln\left(\frac{N_1 - N_0}{N_1 - \left(0.1(N_1 - N_0) + N_0\right)}\right)$$

$$t_{0.9} = \tau_r \ln\left(\frac{N_1 - N_0}{N_1 - \left(0.9(N_1 - N_0) + N_0\right)}\right)$$

$$\boxed{\begin{aligned} t_r &= t_{0.9} - t_{0.1} = \tau_r \ln(0.9/0.1) \\ f_{3dB} &= \frac{1}{2\pi\tau_r} = \frac{1}{2\pi t_r}\ln(0.9/0.1) \end{aligned}}$$

LED Direct Modulation

Maximum Modulation Speed



LED's response time limits the modulation speed

$$f_{3dB,LED} = \frac{1}{2\pi\tau_r} \qquad f_{3dB,NRZ} = \frac{R_B}{2}$$

$$f_{3dB,LED} \geq f_{3dB,NRZ}$$

$$\frac{1}{2\pi\tau_r} \geq \frac{R_B}{2} \rightarrow \boxed{R_B \leq \frac{1}{\pi\tau_r}}$$

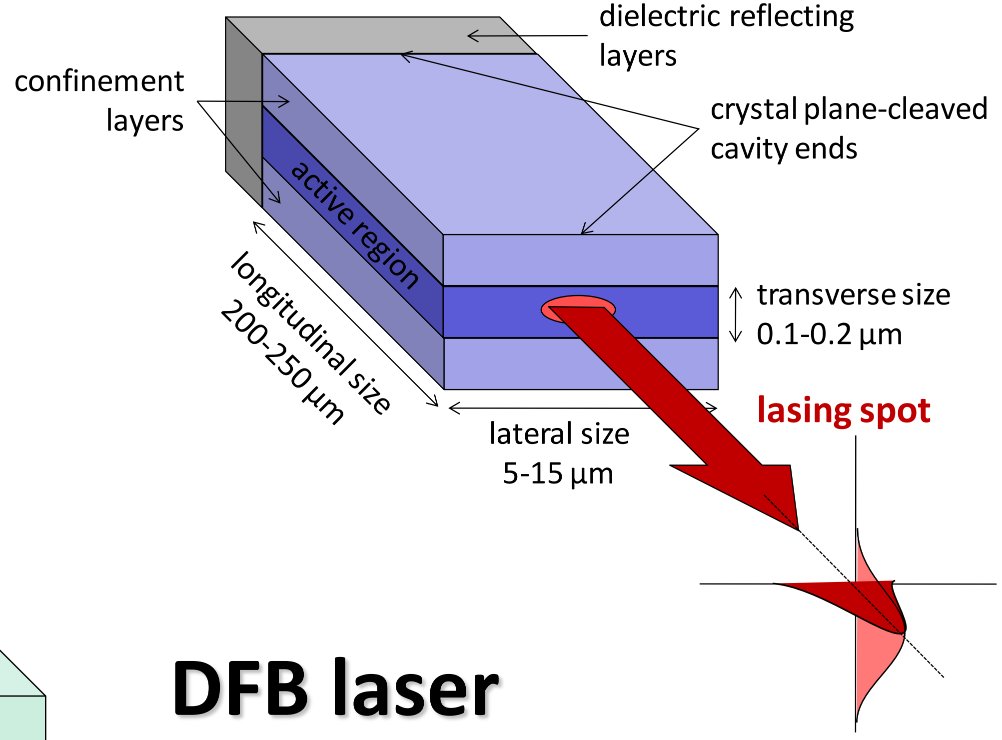
typically: $\tau_r \sim 10\text{ns}$

LASER DIODE

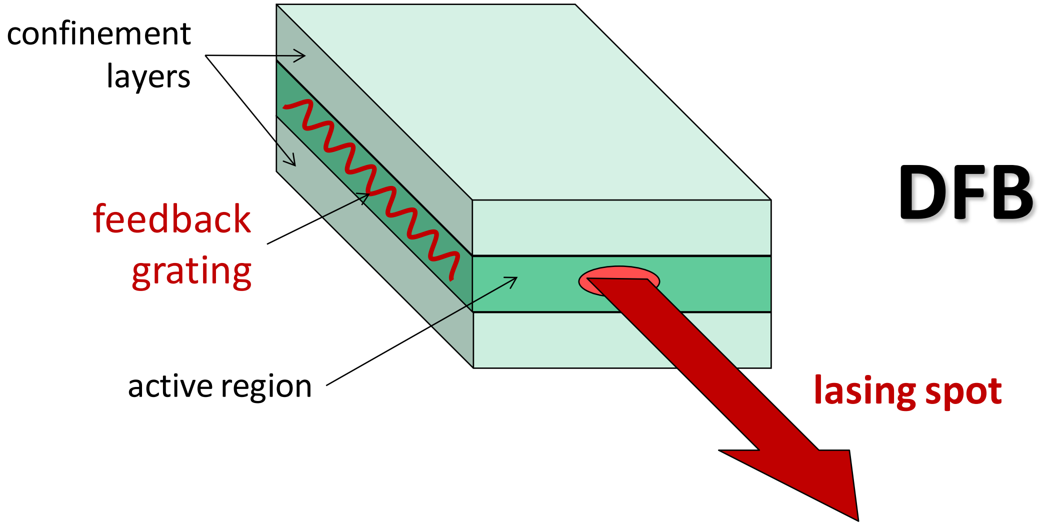
LASER

(Light Amplification by Stimulated Emission of Radiation)

Fabry-Perot resonant cavity

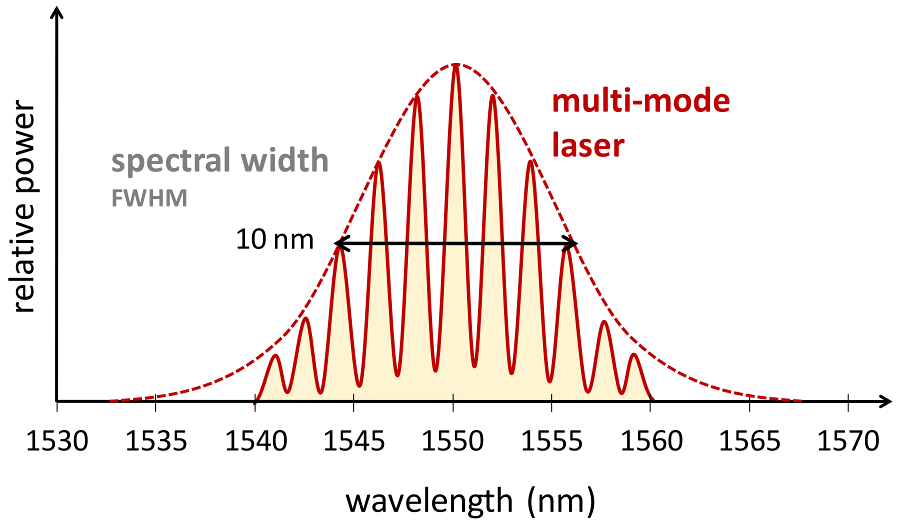


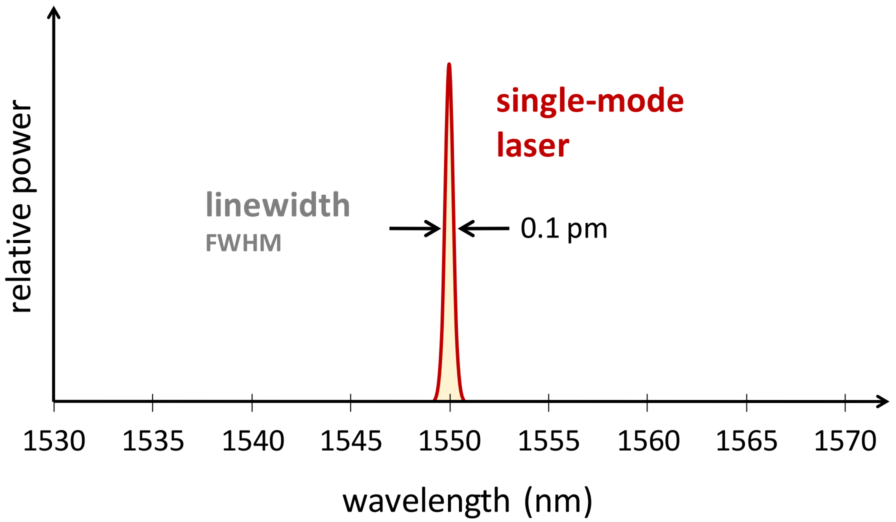
DFB laser



Characteristics Overview

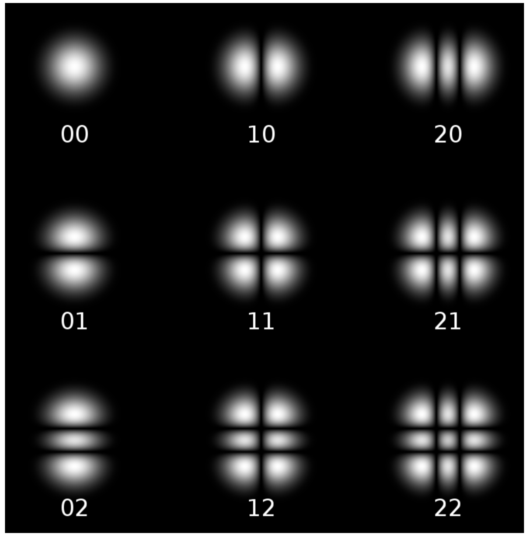
LASER Main Figures





- Single-moded (Transversal)
- $\Delta\lambda$ very narrow → 10 MHz (0.08 pm) for DFB
- P_{OUT} high → 10 dBm (10 mW)
- BW up to 10 GHz → R_B up to 10 Gb/s

Transverse Modes



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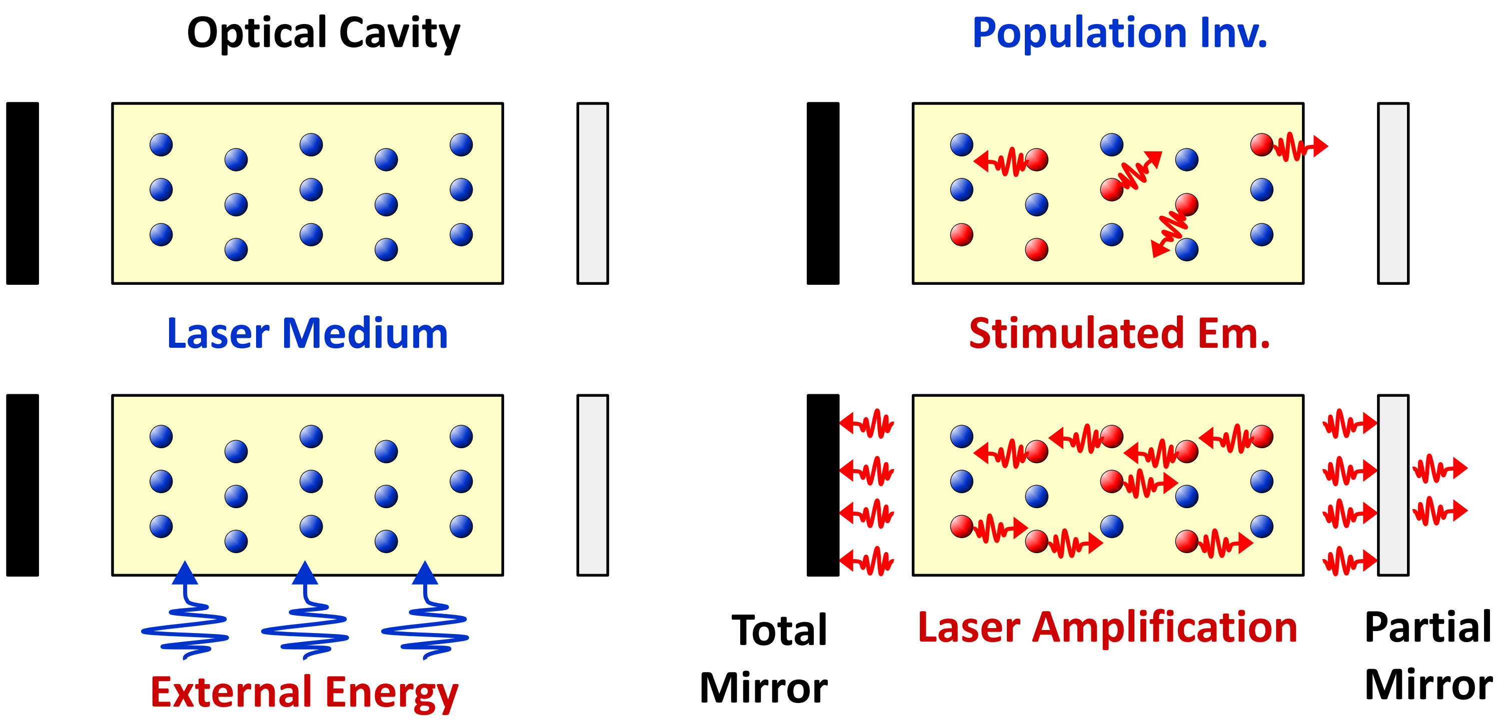
Laser's Working Principle

WORKING PRINCIPLE

"The LASER consists of an optical resonant cavity based on the **stimulated emission** process and provides coherent light"

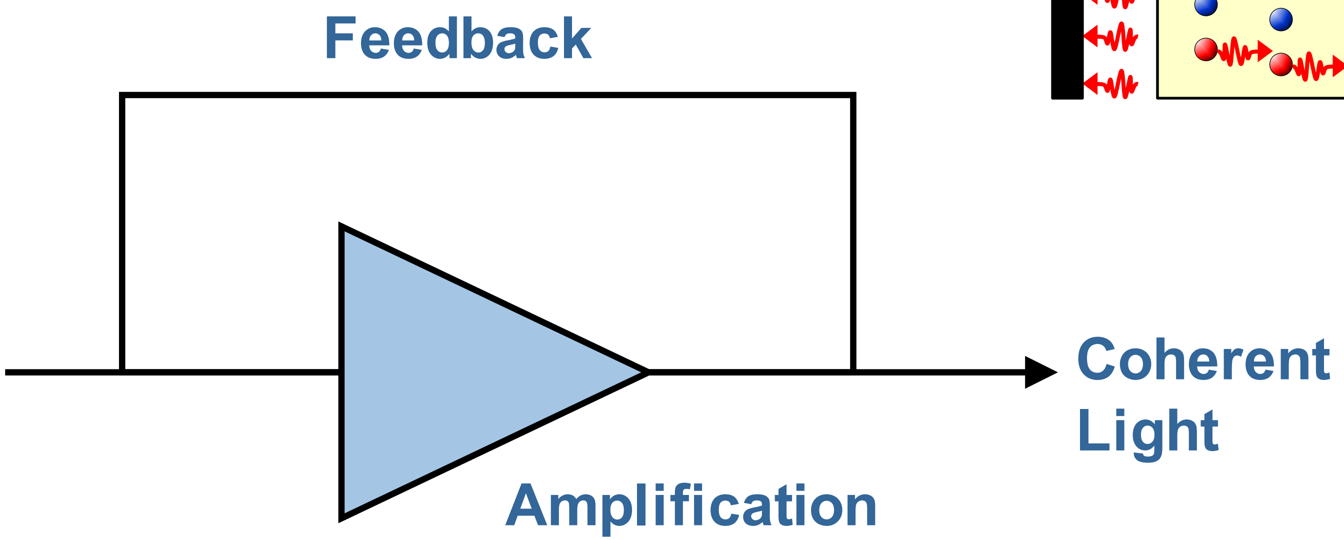


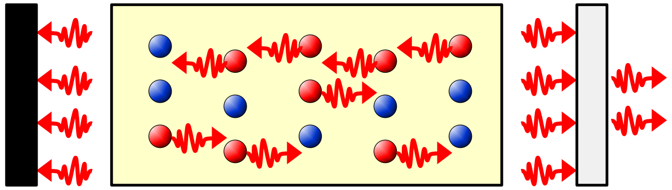
How Lasers Work

Laser's Working Principle

Equivalent Model

"The LASER can be modeled as an amplification system with feed-back"

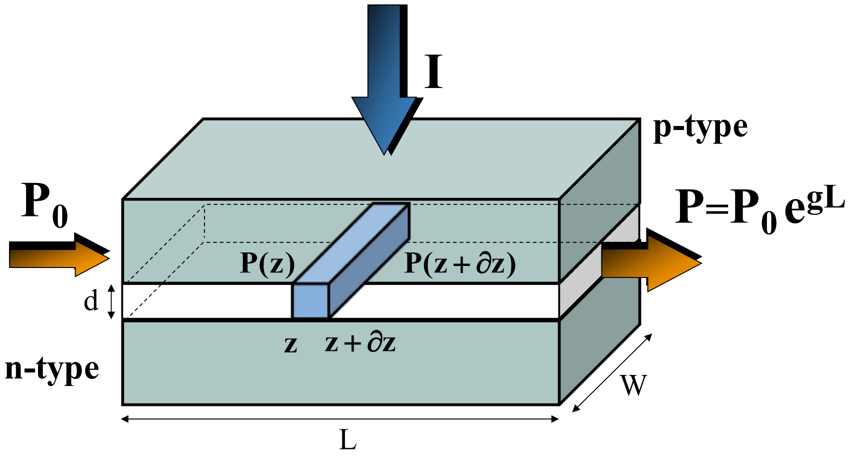


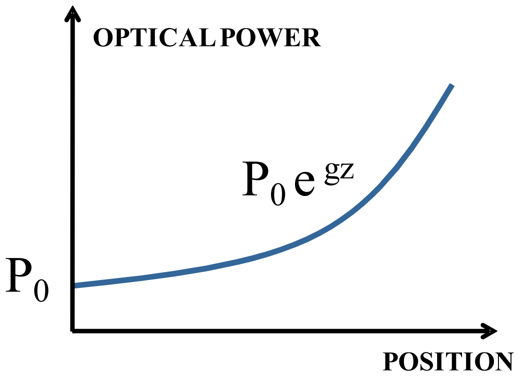


Condition → Gain > Losses

Laser's Working Principle

MATERIAL GAIN



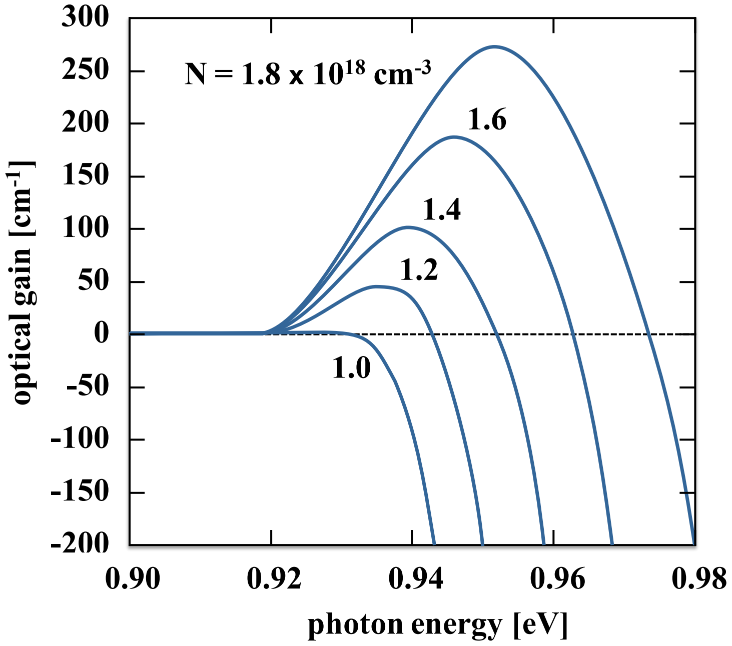


$$\frac{\partial P}{\partial z} = gP$$

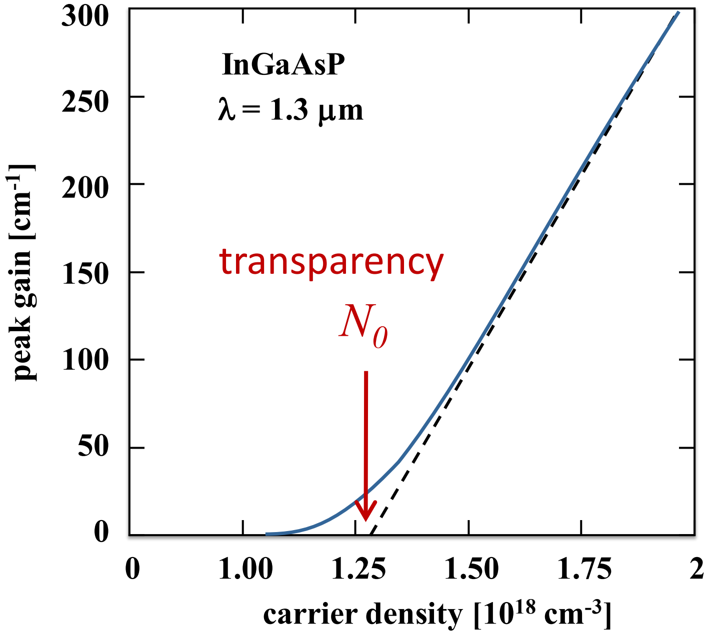
$$\Updownarrow$$

$$P(z) = P_0 e^{gz}$$

$g \equiv$ material unity gain [m^{-1}]



$$\lambda = \frac{hc}{q} E[eV]$$



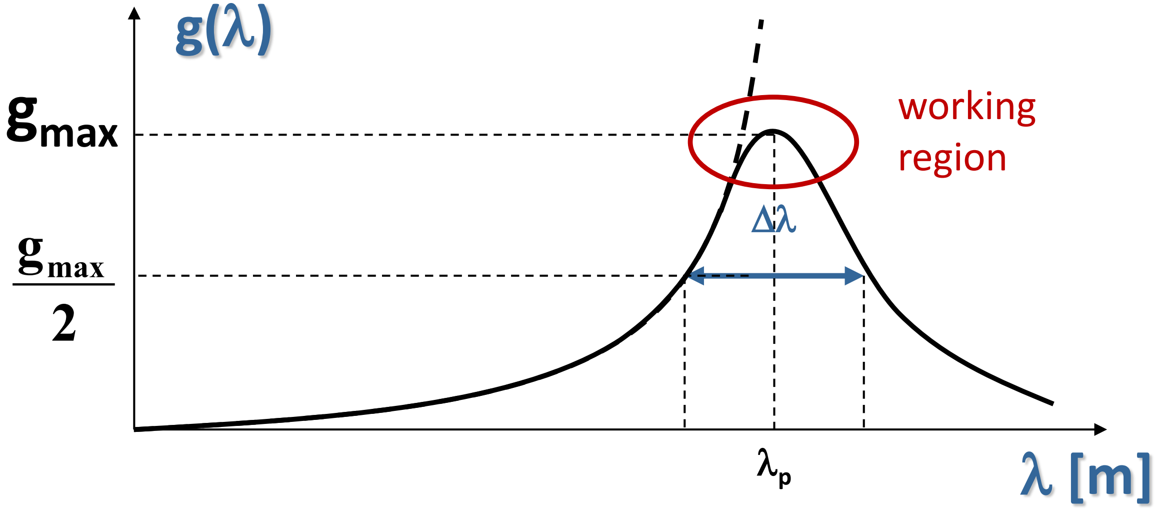
Laser's Working Principle

material unity gain [m^{-1}]

$$\boxed{g = (N_2 - N_1)\frac{\lambda^2}{\tau_r 8\pi n^2}\upsilon(f)}$$

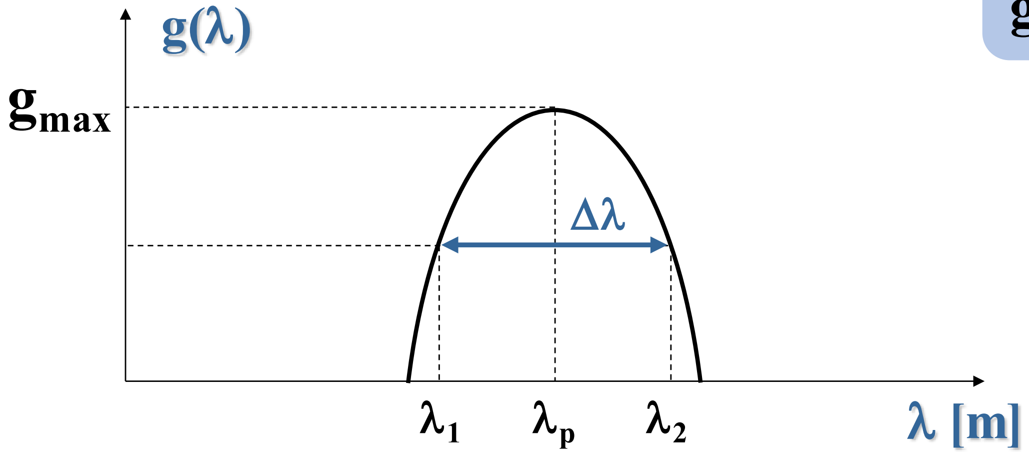
$$g \propto \lambda^2$$

lineshape function $\upsilon(f) \longleftarrow \int_0^\infty \upsilon(f)\partial f = 1$



Material Gain per unit length

mathematical model



$$g_m(N,\lambda) \equiv \overbrace{a(N-N_0)}^{g_p} - \gamma(\lambda-\lambda_p)^2$$ [m^{-1}]

a: gain coefficient
γ: curvature factor
λ_p: peak wavelength
N: carrier density
N_0: transparence level
g_p: peak gain

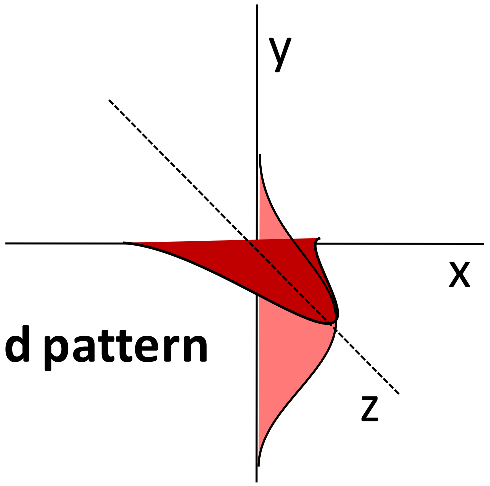
Laser's Working Principle

Confinement Factor

"Energy fraction inside the active region "

$$\Gamma \equiv \frac{E\big|_{AR}}{E\big|_{Total}} \leq 1$$

far field pattern



$$g(\lambda) \equiv \Gamma g_m(\lambda) = \Gamma a(N - N_0) - \Gamma\gamma(\lambda - \lambda_p)^2$$

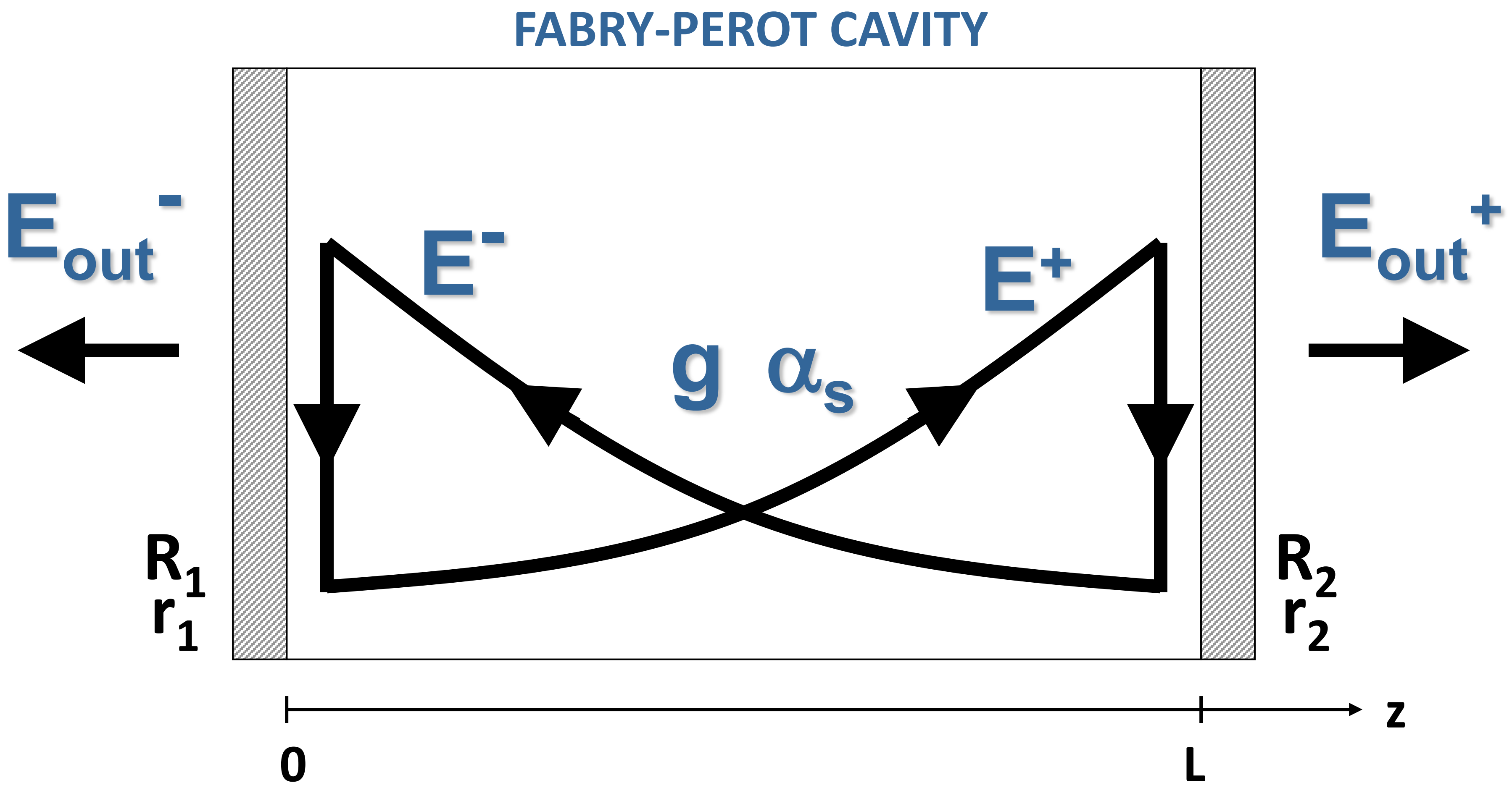
Net Material Gain per unit length

$$\boxed{g_n(\lambda) \equiv g(\lambda) - \alpha_s = \Gamma a(N - N_0) - \Gamma\gamma(\lambda - \lambda_p)^2 - \alpha_s}$$

α_S: Scattering Loss Coef.

Lasing Condition

OSCILLATION CONDITION



R_i: Reflectivity

r_i: Reflectance

g: Material Gain Coef. [m^{-1}]

α_s: Scattering Loss Coef. [m^{-1}]

Lasing Condition

Propagation Equations (plane wave)

$$E^+(z) = E_0^+ \; e^{\frac{1}{2}(g-\alpha_s)z} \; e^{-j\beta z} \; e^{-j\omega t}$$

$$E^-(z) = E_L^- \; e^{\frac{1}{2}(g-\alpha_s)(L-z)} \; e^{-j\beta(L-z)} \; e^{-j\omega t}$$

Boundary Conditions

$$E^+(0) = r_1 E^-(0)$$

$$E^-(L) = r_2 E^+(L)$$

$$E^+(0) = E_0^+ \cancel{e^{-j\omega t}} = r_1 E^-(0) = r_1 \left(E_L^- e^{\frac{1}{2}(g-\alpha_s)L} e^{-j\beta L} \cancel{e^{-j\omega t}} \right) \to E_0^+ = r_1 E_L^- e^{\frac{1}{2}(g-\alpha_s)L} e^{-j\beta L}$$

$$E^-(0) = E_L^- e^{\frac{1}{2}(g-\alpha_s)L} e^{-j\beta L} e^{-j\omega t}$$

$$E^-(L) = E_L^- \cancel{e^{-j\omega t}} = r_2 E^+(L) = r_2 \left(E_0^+ e^{\frac{1}{2}(g-\alpha_s)L} e^{-j\beta L} \cancel{e^{-j\omega t}} \right) \to E_L^- = r_2 E_0^+ e^{\frac{1}{2}(g-\alpha_s)L} e^{-j\beta L}$$

$$E^+(L) = E_0^+ e^{\frac{1}{2}(g-\alpha_s)L} e^{-j\beta L} e^{-j\omega t}$$

$$\cancel{E_0^+} = r_1 r_2 \cancel{E_0^+} e^{(g-\alpha_s)L} e^{-j2\beta L} \to \boxed{r_1 r_2 e^{(g-\alpha_s)L} e^{-j2\beta L} = 1}$$

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Lasing Condition

Modulus Oscillation Condition

$$1 = r_1 r_2 e^{(g_{th}-\alpha_s)L}$$

$$\frac{1}{r_1 r_2} = e^{(g_{th}-\alpha_s)L} \rightarrow \ln\left(\frac{1}{r_1 r_2}\right) = \left(g_{th} - \alpha_s\right)L$$

$$g_{th} = \alpha_s + \frac{1}{L}\ln\left(\frac{1}{r_1 r_2}\right) = \alpha_s + \underbrace{\frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)}_{\alpha_c} \equiv \alpha_t$$

$$R_i = |r_i|^2$$

g_{th}: threshold gain

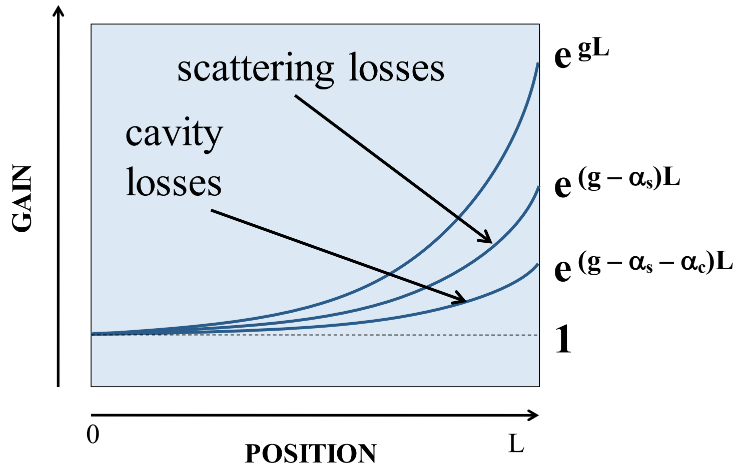
α_c: cavity losses

α_t: total losses

Threshold Gain

[m^{-1}]

$$g \ge g_{th} = \alpha_s + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$

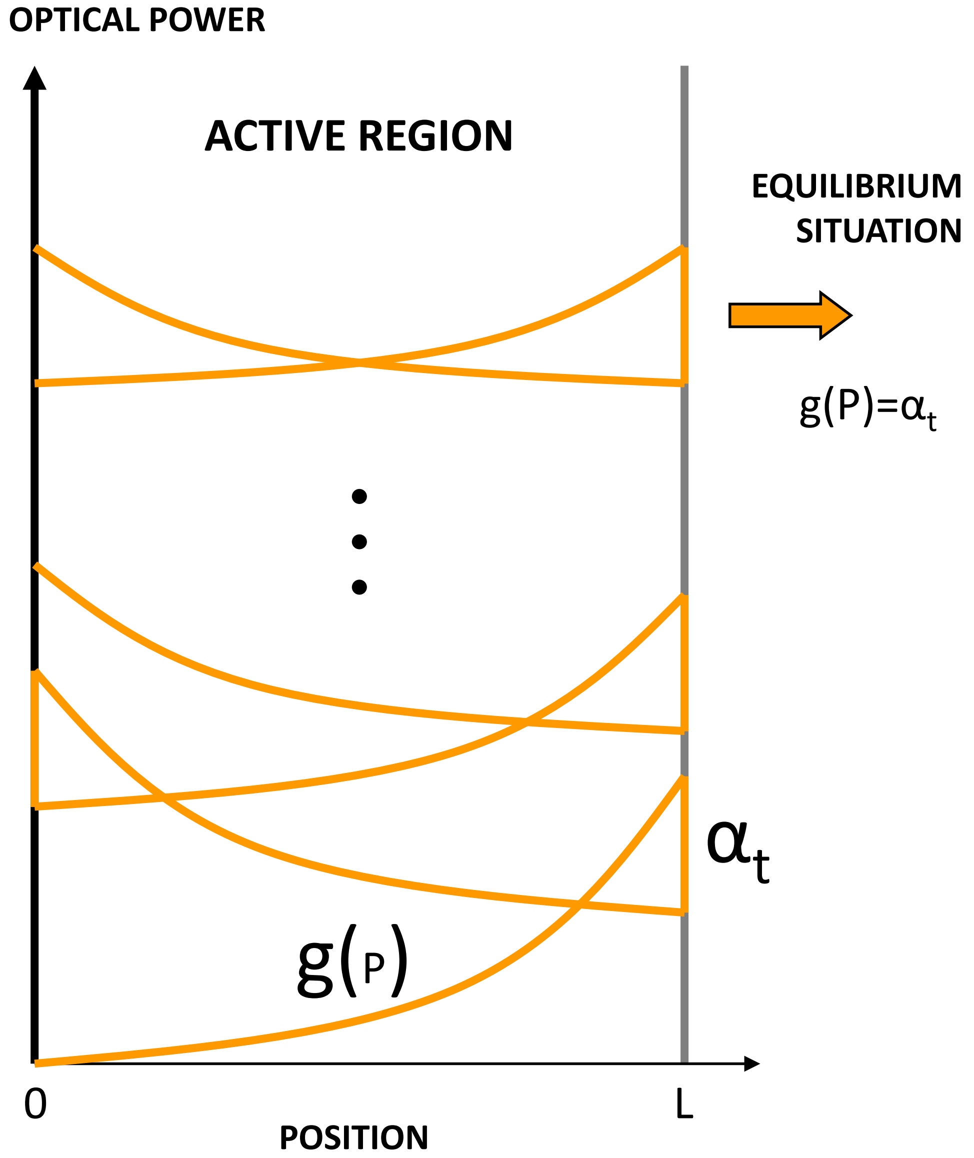


Lasing Condition

Gain Saturation

$$\boxed{g(P) = \frac{g_0}{1 + P/P_{sat}}}$$

- $g < \alpha_t \rightarrow$ Unstable Situation (No Oscillation)
- $g = \alpha_t \rightarrow$ Stable Situation (Oscillation)
- $g > \alpha_t \rightarrow$ Unstable Situation (Saturation)



Lasing Condition

Phase Oscillation Condition

$$1 = e^{-j2\beta L}$$

$$2\beta L = m \cdot 2\pi \rightarrow 2\frac{2\pi}{\lambda} nL = m \cdot 2\pi \rightarrow L = m\frac{\lambda_m}{2n} = m\frac{c}{2nf_m}$$

$$\boxed{f_m = m\frac{c}{2nL}}$$

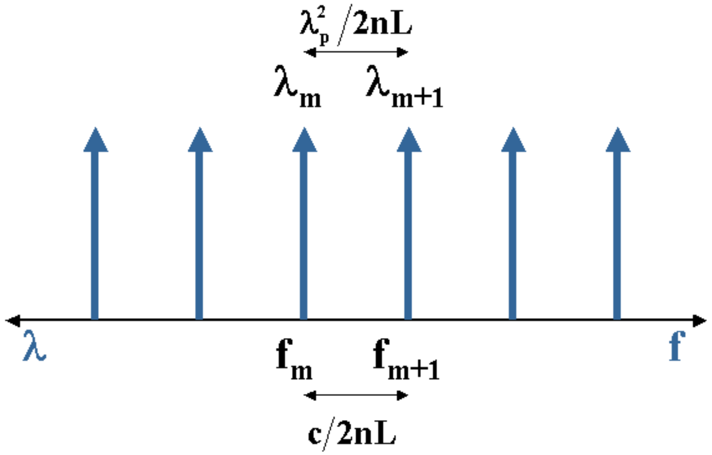
Cavity Resonance Frequencies

Oscillation Modes (longitudinal)

$$\Delta f = \frac{c}{2nL}$$

$$\frac{\Delta\lambda}{\lambda_p} \approx \frac{\Delta f}{f_p}$$

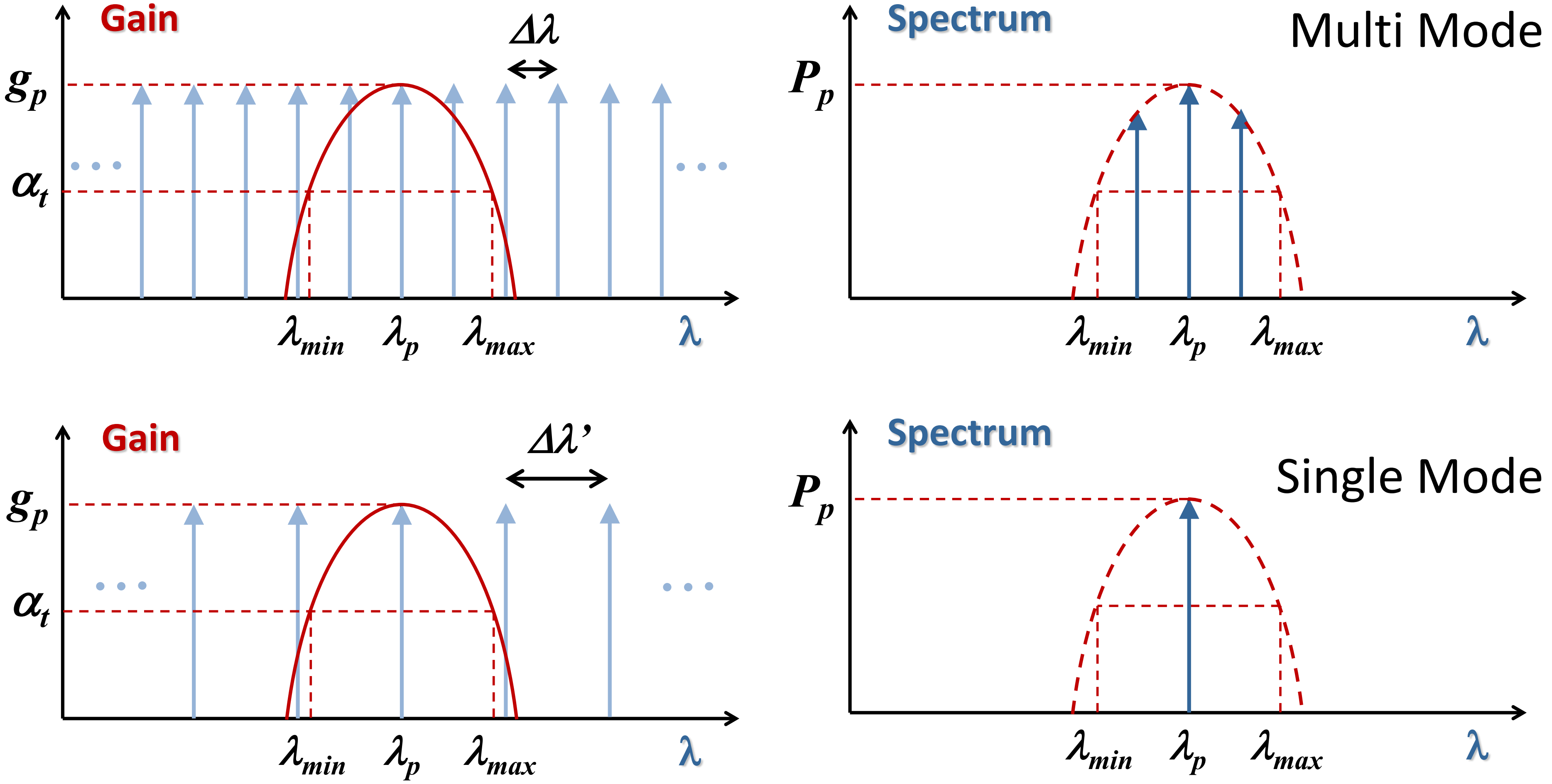
$$\Delta\lambda \approx \Delta f \cdot \frac{\lambda_p^2}{c} = \frac{\lambda_p^2}{2nL}$$



$$L \downarrow \rightarrow \Delta f \uparrow \rightarrow \Delta\lambda \uparrow$$

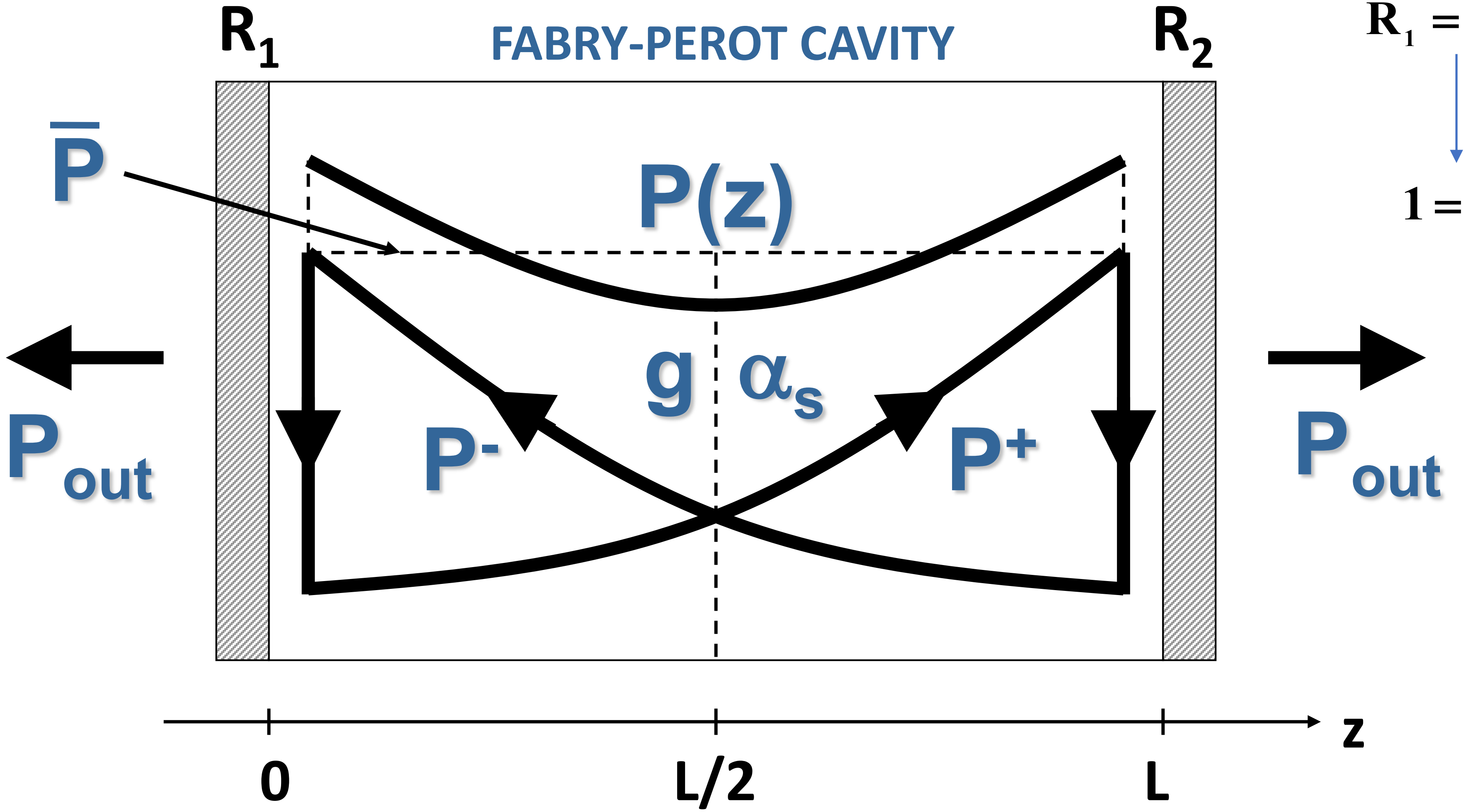
Lasing Condition

Combined Effect $\begin{cases} g(\lambda) \geq g_{th} \\ \Delta\lambda \end{cases}$



Light Emission

Optical Power in the Laser Cavity



Symmetric Cavity

$$R_1 = R_2 = R$$

Gain condition

$$1 = Re^{g_n L}$$

Light Emission

$$P(z) = P^+(z) + P^-(z) = P_0\left[e^{g_n z} + e^{g_n[L-z]}\right] = P_0 e^{g_n L/2}\left[e^{g_n[z-L/2]} + e^{g_n[L/2-z]}\right]$$

$$P^+(z) = P_0 e^{g_n z} \qquad e^{g_n[z-L/2]} \approx 1 + g_n[z-L/2]$$

$$P^-(z) = P_0 e^{g_n[L-z]} \qquad e^{g_n[L/2-z]} \approx 1 + g_n[L/2-z] = 1 - g_n[z-L/2]$$

$$\boxed{P(z) \approx P_0 e^{g_n L/2}\left[1 + \cancel{g_n[z-L/2]} + 1 - \cancel{g_n[z-L/2]}\right] = 2P_0 e^{g_n L/2} \equiv \overline{P}}$$

$$P_{out} = P_0 e^{g_n L}(1-R) \approx \frac{\overline{P}}{2e^{g_n L/2}} e^{g_n L}(1-R) = \frac{\overline{P}}{2} e^{g_n L/2}(1-R) = \frac{\overline{P}}{2}\frac{1-R}{\sqrt{R}}$$

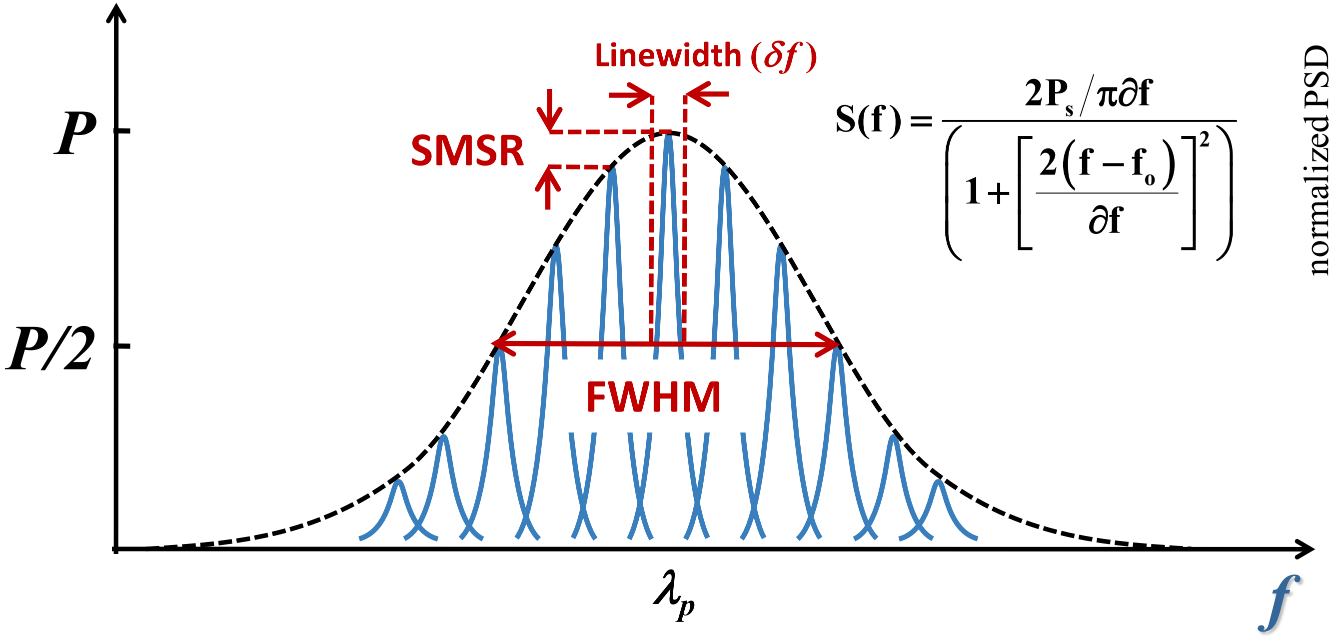
$$R e^{g_n L} = 1 \rightarrow e^{g_n L} = \frac{1}{R} \rightarrow e^{g_n L/2} = \frac{1}{\sqrt{R}}$$

m modes $\longrightarrow$

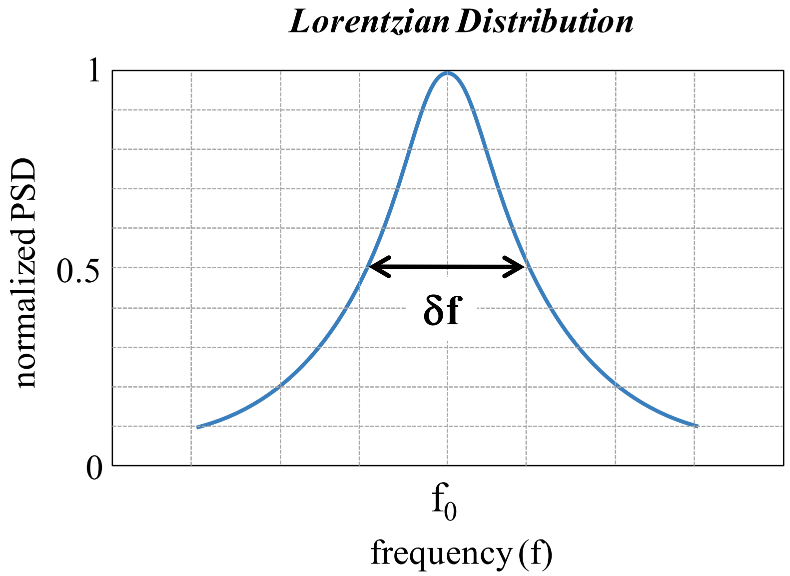
$$P_{out} = \sum_m P_{out,m} \approx \sum_m \frac{1-R}{2\sqrt{R}} \overline{P}_m$$

Light Emission

OPTICAL POWER SPECTRUM



$$S(f) = \frac{2P_s/\pi\partial f}{\left(1 + \left[\frac{2(f - f_o)}{\partial f}\right]^2\right)}$$



Finesse $F \equiv \dfrac{\Delta f}{\partial f}$

1. $\Delta f = \dfrac{c}{2nL} \qquad \Delta\lambda \approx \dfrac{\lambda_p^2}{2nL}$ (resonance frequencies>)

2. $g \geq g_{th} = \alpha_s + \dfrac{1}{2L}\ln\left(\dfrac{1}{R_1R_2}\right)$ (gain condition)

Laser Dynamics

LASER DYNAMICS

"Carrier and Photons concentration can be modeled using two coupled rate equations"

$$\left\{\begin{array}{c}\text{carrier}\\\text{variation}\end{array}\right\} = \left\{\begin{array}{c}\text{carrier}\\\text{generation}\\\text{rate}\end{array}\right\} - \left\{\begin{array}{c}\text{spont.}\\\text{emission}\\\text{rate}\end{array}\right\} - \left\{\begin{array}{c}\text{stimul.}\\\text{emission}\\\text{rate}\end{array}\right\}$$

$$\left\{\begin{array}{c}\text{photon}\\\text{variation}\end{array}\right\} = \left\{\begin{array}{c}\text{stimul.}\\\text{emission}\\\text{rate}\end{array}\right\} - \left\{\begin{array}{c}\text{photon}\\\text{losses}\\\text{rate}\end{array}\right\} + \left\{\begin{array}{c}\text{spont.}\\\text{emission}\\\text{fraction}\end{array}\right\}$$

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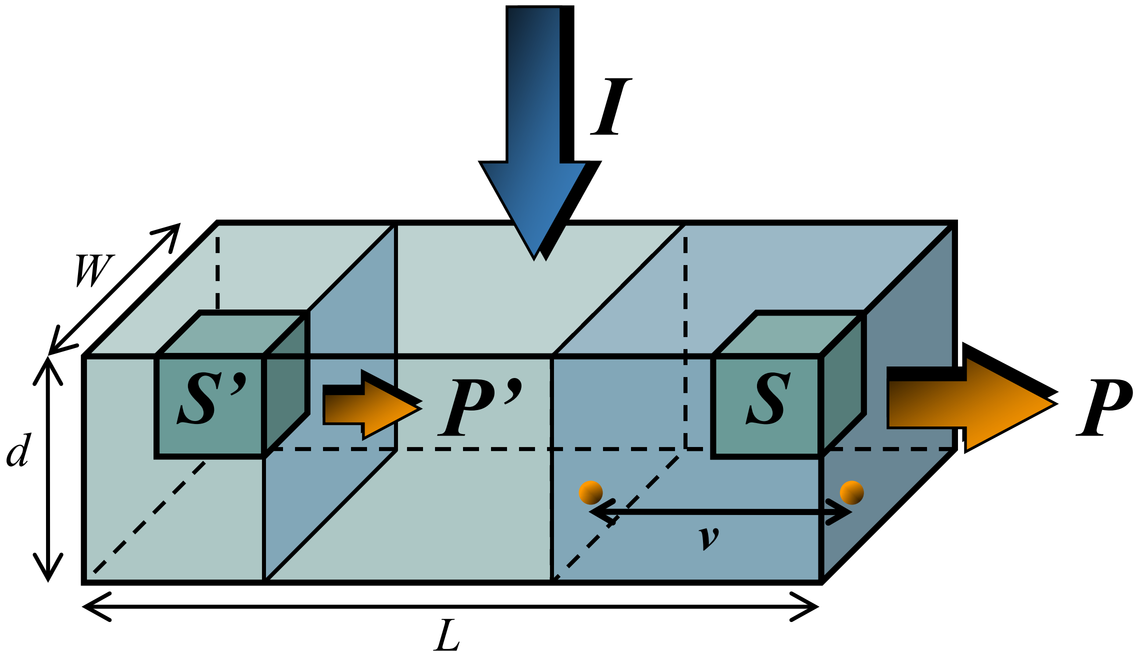
Light Emission

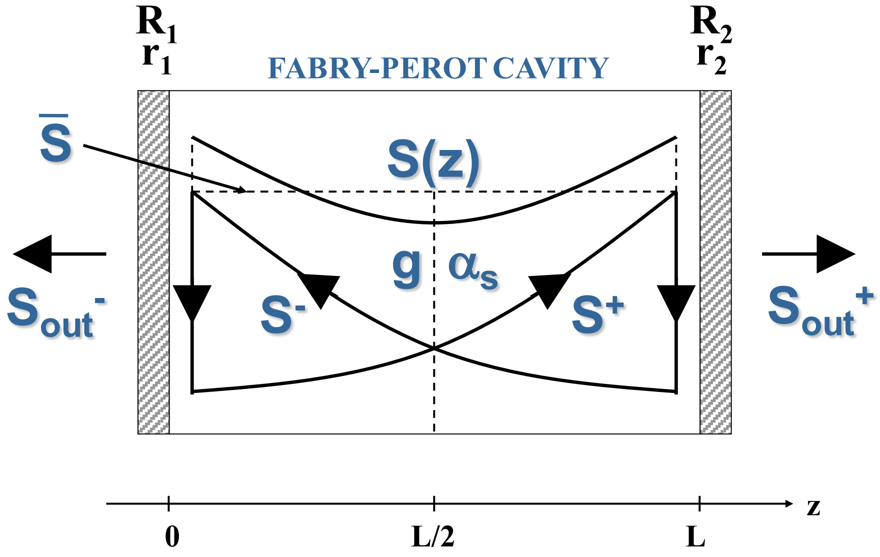
Photon Density – Optical Power Relationship



$$\frac{\text{Fotons}}{\text{sec.}} = \frac{P\,[J/s]}{hf\,[J]}$$

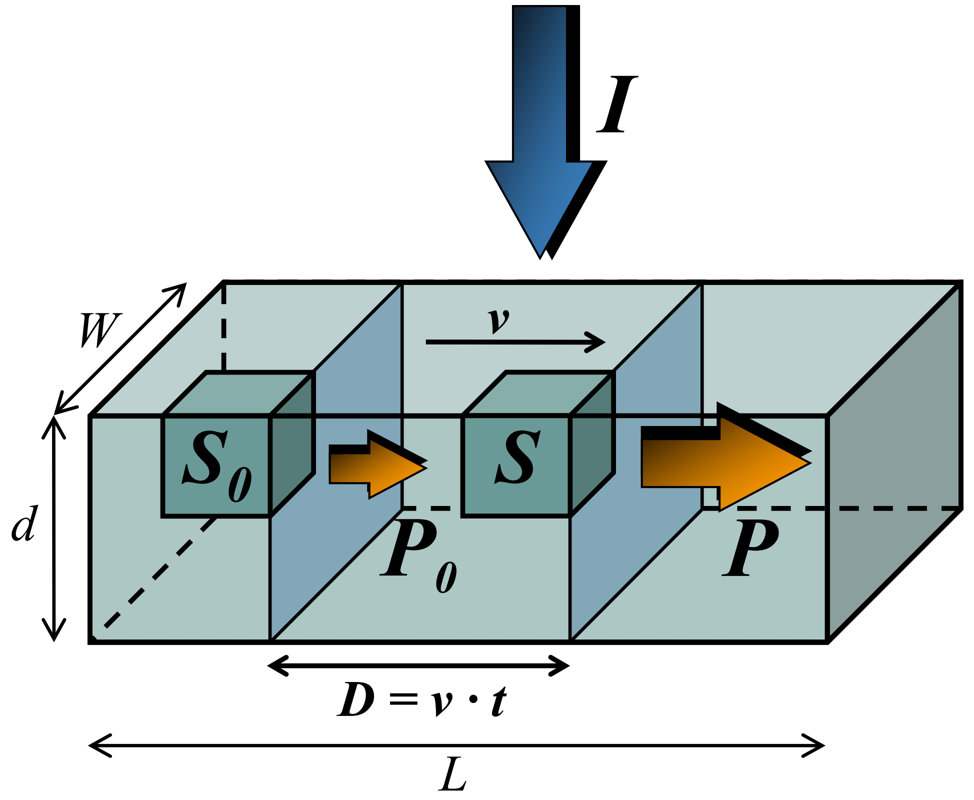
Photon Density in the Active Region

$$S\,[m^{-3}] = \frac{P\,[J/s]}{hf\,[J] \times \frac{c}{n}\,[m/s] \times Wd\,[m^2]}$$



Laser Dynamics

Temporal evolution of Photon Density



$$\frac{\partial P}{\partial t} = vg\,P$$

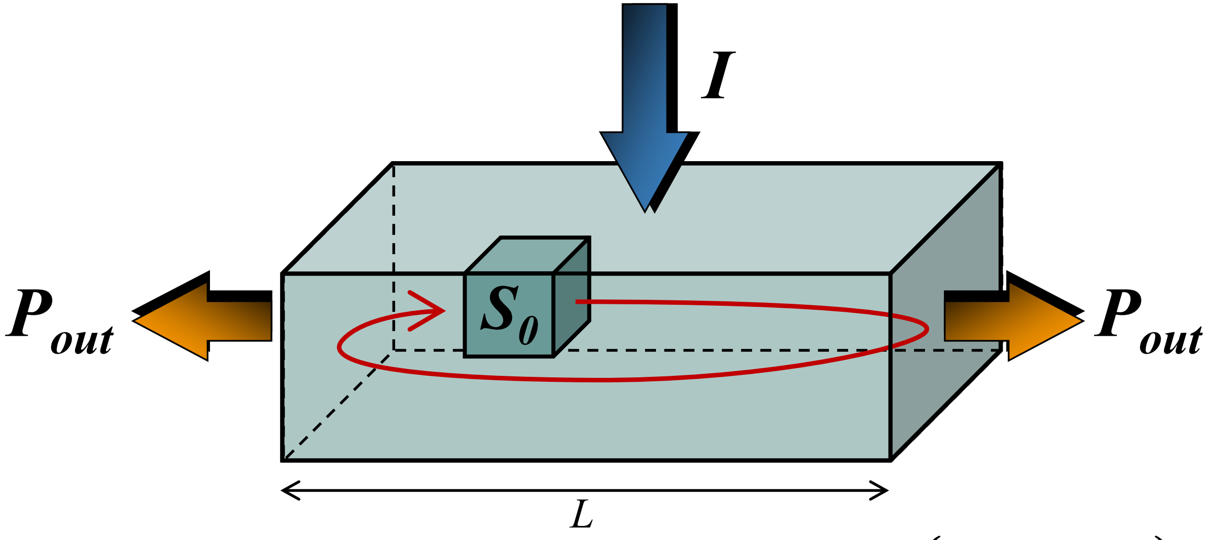
$$\frac{\partial S}{\partial t} = vg\,S$$

$$P = P_0\, e^{gD} = P_0\, e^{g \cdot v \cdot t} \longrightarrow \frac{\partial P}{\partial t} = g\, v\, P_0\, e^{g \cdot v \cdot t} = g\, v\, P$$

$$S = \frac{P}{hf \cdot v \cdot Wd} \longrightarrow \frac{\partial S}{\partial t} = \frac{1}{hf \cdot v \cdot Wd}\frac{\partial P}{\partial t} = \frac{1}{hf \cdot v \cdot Wd} vgP = vgS$$

Laser Dynamics

Photon Variation in the Cavity



$$S = S_0\, e^{(g-\alpha_s)2L} R^2 = S_0\, e^{(g-\alpha_s)2L} e^{-2\ln\frac{1}{R}} = S_0\, e^{\left(g-\alpha_s-\frac{1}{L}\ln\frac{1}{R}\right)2L} = S_0\, e^{(g-\alpha_t)2L}$$

$$R^2 = e^{2\ln R} = e^{-2\ln\frac{1}{R}}$$

$$\alpha_t \equiv \alpha_s + \underbrace{\frac{1}{L}\ln\frac{1}{R}}_{\alpha_c}$$

$$S(z) = S_0\, e^{(g-\alpha_t)d} \xrightarrow{d=v\cdot t} S(t) = S_0\, e^{(g-\alpha_t)v\cdot t}$$

$$\Rightarrow \boxed{\frac{\partial S(t)}{\partial t} = v\left(g-\alpha_t\right)\cdot S_0\, e^{(g-\alpha_t)v\cdot t} = v\left(g-\alpha_t\right)\cdot S(t)}$$

Laser Dynamics

LASER'S RATE EQUATIONS

Carriers ⇨

$$\frac{\partial N}{\partial t} = \frac{I}{qV} - \frac{N}{\tau_r} - v\sum_{i=1}^{M} g_i S_i \qquad [m^{-3}s^{-1}]$$

Photons ⇨

$$\frac{\partial S_i}{\partial t} = v \cdot g_i S_i - v \cdot \alpha_t S_i + \beta \frac{N}{\tau_r} \qquad [m^{-3}s^{-1}]$$

photon lifetime

$$\tau_p \equiv \frac{1}{v \cdot \alpha_t} \qquad [s]$$

N: carrier density in the AR
S: photon density in the AR
g_i: mode's gain parameter
M: number of long. modes

I: electrical current intensity
τ_r: carrier lifetime
β: spontaneous emission coeff.
α_t: cavity's total losses

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Laser Dynamics

Static Behavior

$$\frac{\partial N}{\partial t} = \frac{I}{qV} - \frac{N}{\tau_r} - v \cdot gS = 0$$

$$\frac{\partial S}{\partial t} = v \cdot gS - v \cdot \alpha_t S + \cancel{\beta \frac{N}{\tau_r}} = 0$$

single-mode cavity (M=1)

stationary regime $\frac{\partial}{\partial t} = 0$

$\beta \ll$

$$v \cdot gS - v \cdot \alpha_t S = 0 \rightarrow g = \alpha_t$$

$$\lambda_{emission} = \lambda_p$$

$$g = \Gamma a (N - N_0) - \cancel{\Gamma\gamma(\lambda - \lambda_p)^2}$$

$$\Gamma a (N - N_0) = \alpha_t \rightarrow \boxed{N = N_0 + \frac{\alpha_t}{\Gamma a}}$$

$$+ \quad \frac{I}{qV} - \frac{N}{\tau_r} - v \cdot \alpha_t S = 0$$

$$\tau_p \equiv \frac{1}{v \cdot \alpha_t}$$

$$\boxed{S = \frac{I}{v \cdot \alpha_t qV} - \frac{N}{v \cdot \alpha_t \tau_r} = \frac{I}{qV}\tau_p - \frac{\tau_p}{\tau_r} N = \frac{I}{qV}\tau_p - \frac{\tau_p}{\tau_r}\left[N_0 + \frac{\alpha_t}{\Gamma a}\right]}$$

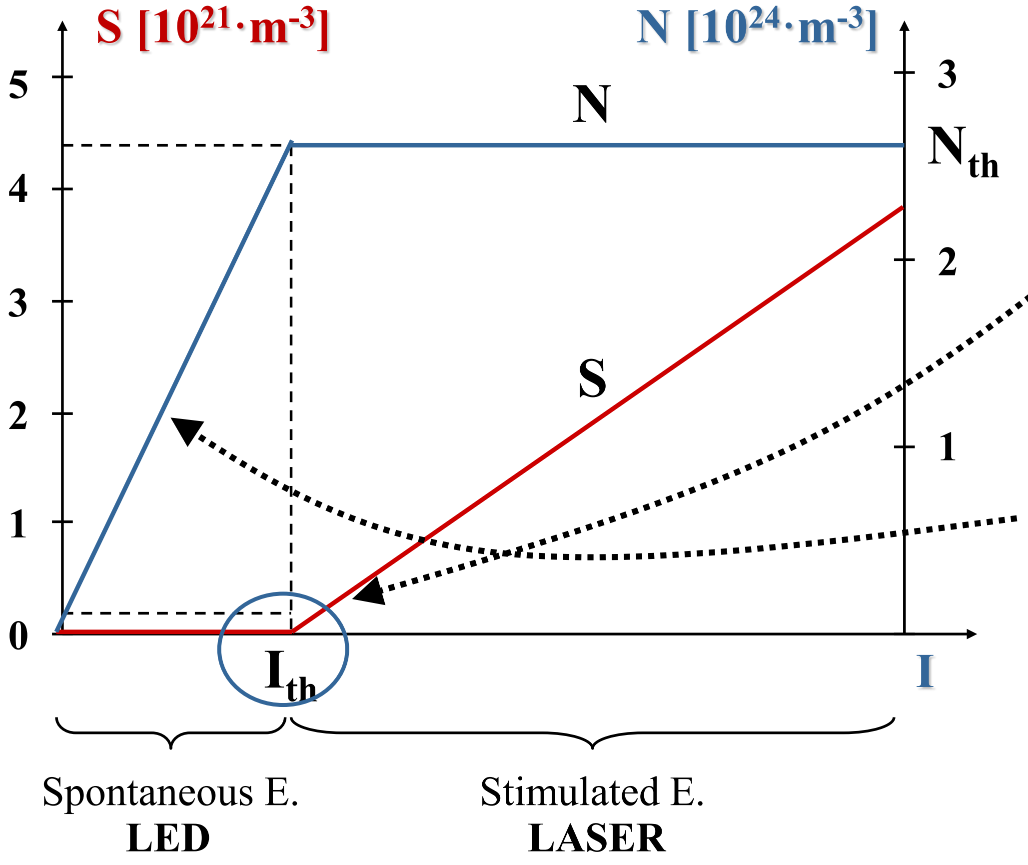
Laser Dynamics

Carriers Constant with J

$$N = N_0 + \frac{\alpha_t}{\Gamma a} \equiv N_{th}$$ [m^{-3}]

Photons Lineal with I

$$S = \frac{I}{qV}\tau_p - \frac{\tau_p}{\tau_r}\underbrace{\left[N_0 + \frac{\alpha_t}{\Gamma a}\right]}_{N_{th}}$$ [m^{-3}]



inflexion point

$S = 0$

$N = N_{th}$

LED behavior

$$\frac{I}{qV} = \frac{N}{\tau_r} \rightarrow \frac{I_{th}}{qV} = \frac{N_{th}}{\tau_r}$$

I_{th}: threshold current

N_{th}: threshold carrier density

Laser Dynamics

Laser Activation Condition

$$S = 0 \rightarrow \frac{I_{th}}{qV} = \frac{N_{th}}{\tau_r} \rightarrow \boxed{I_{th} = \frac{qV}{\tau_r} N_{th} = \frac{qV}{\tau_r}\left[N_0 + \frac{\alpha_t}{\Gamma a}\right]}$$

Threshold Current

$$I \geq \frac{qV}{\tau_r}\left[N_0 + \frac{\alpha_t}{\Gamma a}\right] = \underbrace{\frac{qV}{\tau_r} N_0}_{\text{transparency}} + \underbrace{\frac{qV}{\tau_r}\frac{\alpha_t}{\Gamma a}}_{\text{cavity}}$$

The minimum current has to compensate for the Medium's Transparency and Cavity Losses

Photon Density

$$\boxed{S = \frac{I}{qV}\tau_p - \frac{\tau_p}{\tau_r}\left[N_0 + \frac{\alpha_t}{\Gamma a}\right] = \frac{I}{qV}\tau_p - \frac{I_{th}}{qV}\tau_p = \frac{\tau_p}{qV}\left[I - I_{th}\right]}$$

$$I_{th} = \frac{qV}{\tau_r}\left[N_0 + \frac{\alpha_t}{\Gamma a}\right] \rightarrow \frac{1}{\tau_r}\left[N_0 + \frac{\alpha_t}{\Gamma a}\right] = \frac{I_{th}}{qV}$$

Laser Dynamics

Output Optical Power

$$P_{out} = \left(\left(1-R\right)/2\sqrt{R}\right)\cdot \underbrace{S\cdot v\cdot W\cdot d\cdot hf}_{\bar{P}}$$

$$I \geq I_{th} \qquad \tau_p \equiv \frac{1}{v\cdot\alpha_t}$$

$$S \approx \frac{\tau_p}{qV}\left(I - I_{th}\right)$$

$$N = N_{th}$$

$$\boxed{P_{out} = \left(\left(1-R\right)/2\sqrt{R}\right)\frac{hf}{q\alpha_t L}\left(I - I_{th}\right)}$$

Influence of the active region's length

$$P_{out} = \left(\left(1-R\right)/2\sqrt{R}\right)\frac{hf}{q\alpha_t \cancel{L}}W\cancel{L}\left(J - J_{th}\right) \xrightarrow{L\to 0} 0$$

$$J \equiv \frac{I}{WL}$$

$$\alpha_t \equiv \alpha_s + \frac{1}{L}\ln\frac{1}{R} \xrightarrow{L\to 0} \infty$$

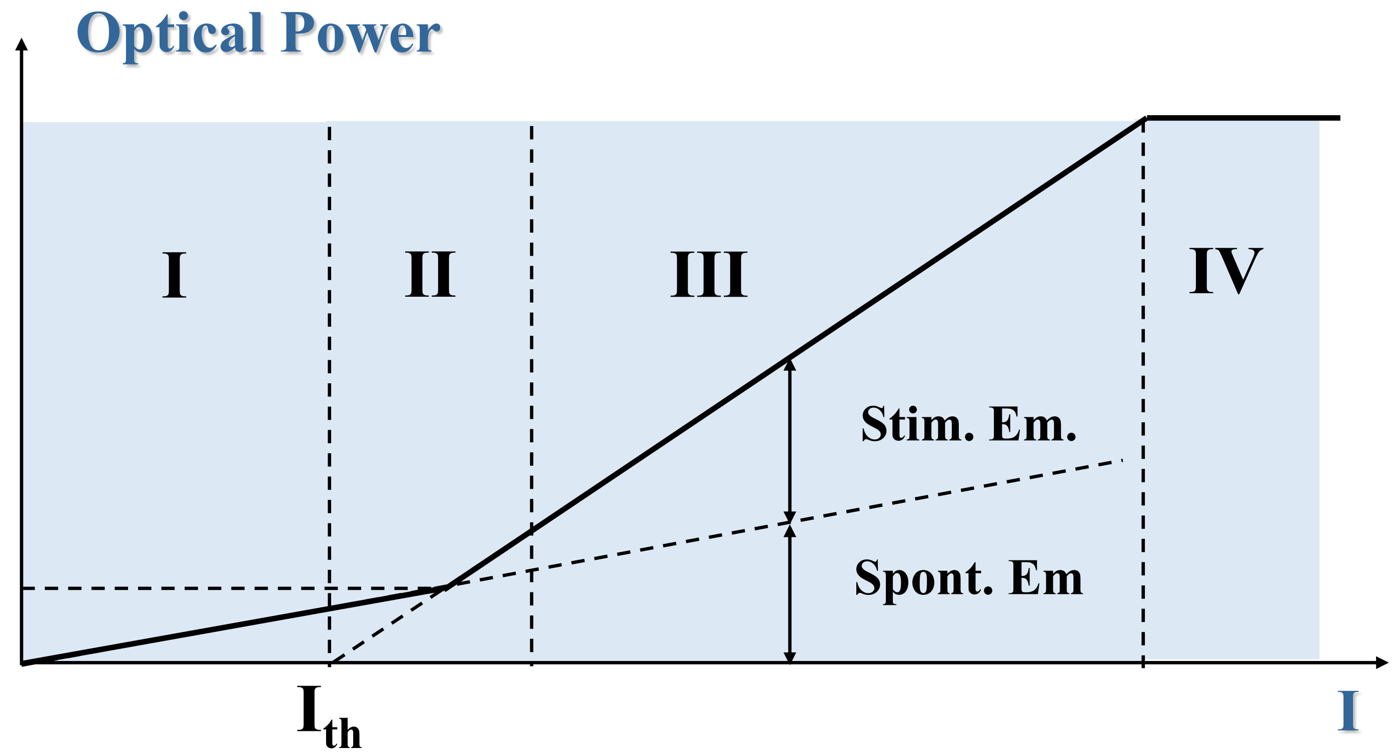
$$J_{th} = \frac{qd}{\tau_r}\left[N_0 + \frac{\alpha_t}{\Gamma a}\right] \xrightarrow{L\to 0} \infty$$

P-Δλ tradeoff

$$L\uparrow \rightarrow \begin{matrix} P\uparrow \\ \Delta\lambda\downarrow \end{matrix}$$

Light Emission

LIGHT-CURRENT CHARACTERISTIC



I → LED-like light, Spontaneous Emission

II → Amplified LED-like light, Amplified Spont. Em.

III → Laser Effect , Coherent Light, Spontaneous Em.

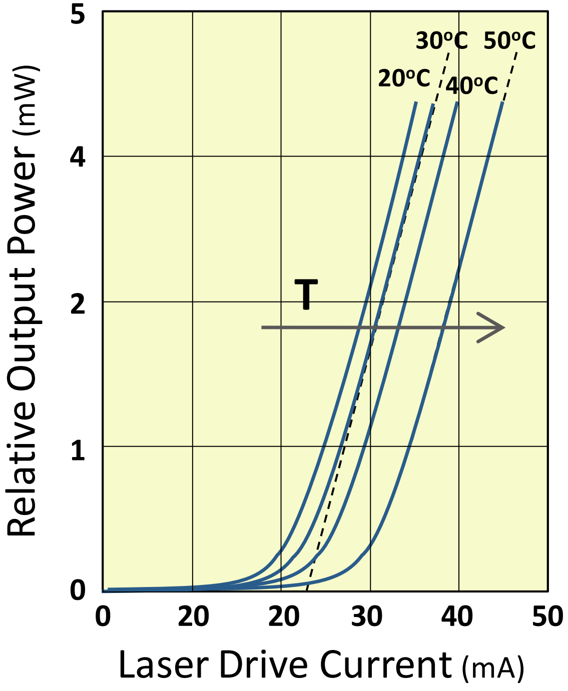
IV → Saturation

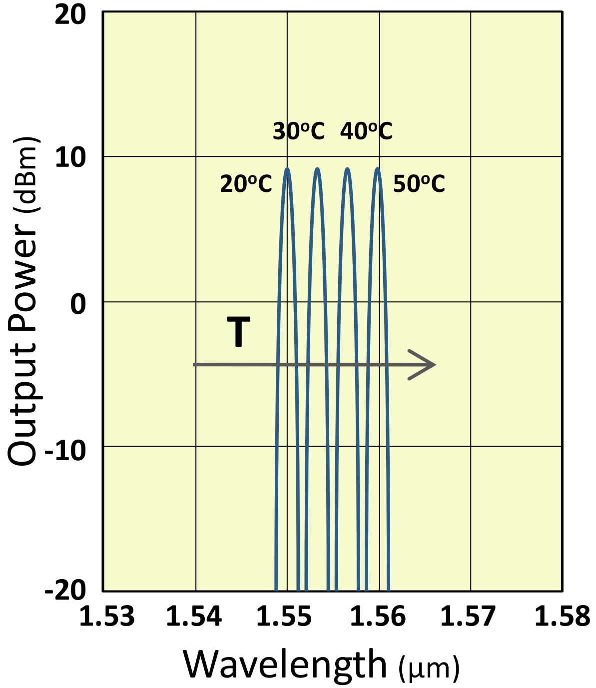
Laser Dynamics

Temperature Effect

Threshold Current & Optical Power

$$T\uparrow \longrightarrow I_{th}\uparrow\ ,\quad P_{out}\downarrow$$





Wavelenth / frequency

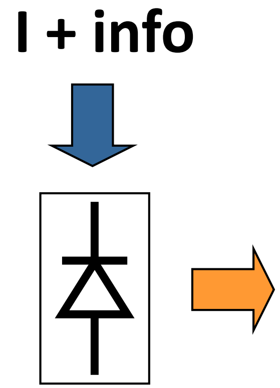
$$T\uparrow \longrightarrow \lambda_c\uparrow\ ,\quad f_c\downarrow$$

Laser
Direct Modulation

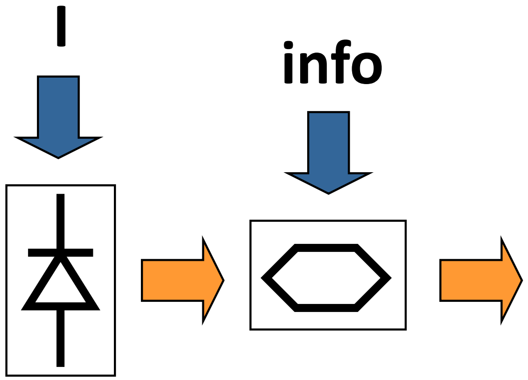
LASER'S DIRECT MODULATION

Modulation Techniques

- **Direct Modulation**



- **External Modulation**



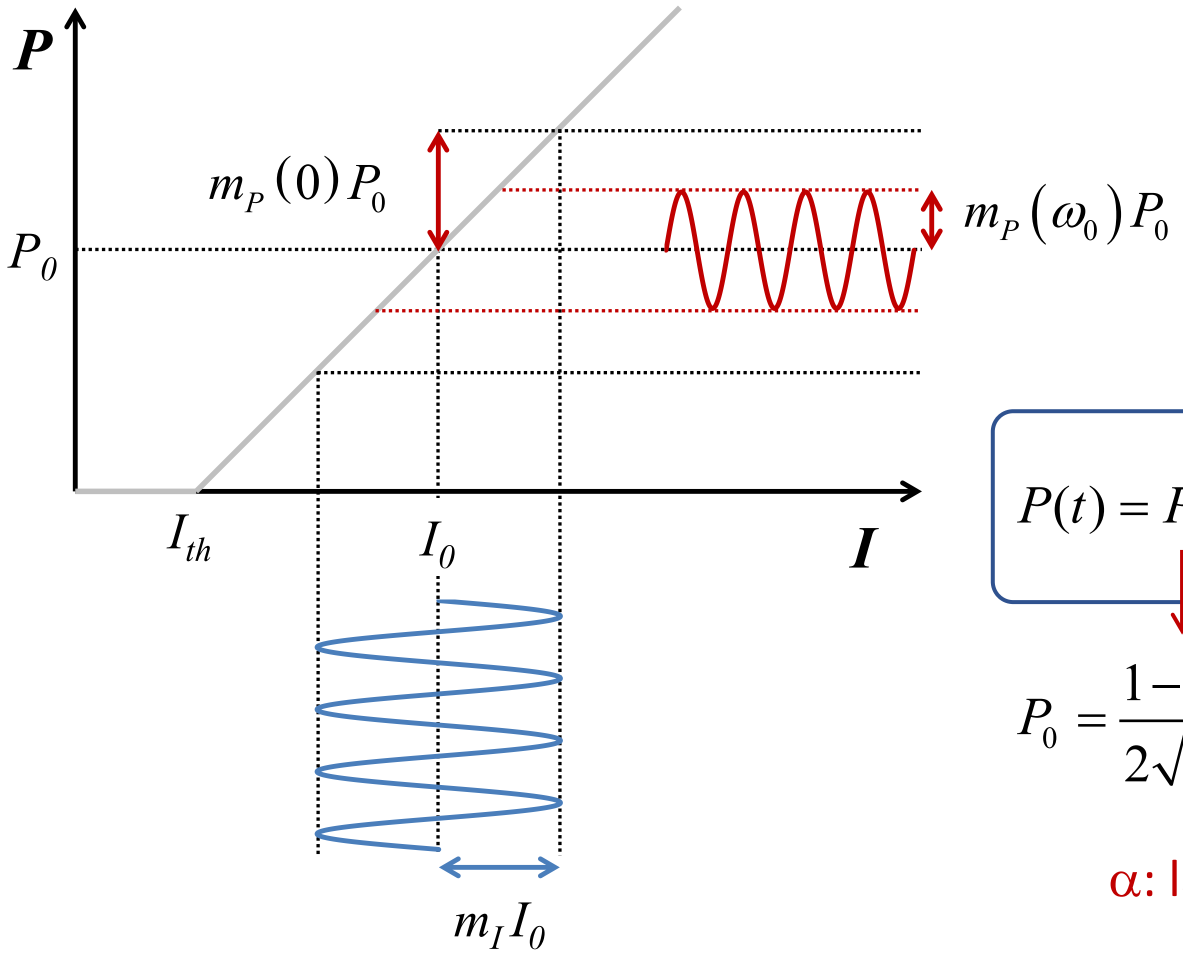
- **Intensity Modulation** (direct detection) ⇒ optical power (IM)
- **Field Modulation** (coherent detection) ⇒
  - amplitude (ASK)
  - frequency (FSK)
  - phase (PSK)

Laser Direct Modulation

Laser Transfer Function – Small Signal Analysis

$$\frac{\partial N}{\partial t} = \frac{I}{qV} - \frac{N}{\tau_r} - v \cdot gS$$

$$\frac{\partial S}{\partial t} = v \cdot gS - v \cdot \alpha_t S$$



$$P(t) = P_0\left(1 + \overbrace{\frac{I_0}{I_0 - I_{th}} m_I \underbrace{\frac{\omega_c^2}{\omega_c^2 - \omega_0^2 + j2\alpha\omega_0}}_{M(\omega_0)}}^{m_P(\omega_0)} e^{j\omega_0 t}\right)$$

$$P_0 = \frac{1-R}{2\sqrt{R}} \frac{1}{\alpha_t L} \frac{hf}{q}\left(I_0 - I_{th}\right)$$

α: laser damping factor

$$2\alpha = \frac{1}{\tau_r} + \tau_p \omega_c^2$$

ω_c: laser resonance frequency

$$\omega_c^2 = \frac{v\Gamma a}{qV}\left(I_0 - I_{th}\right)$$

Small Signal
$m_I << 1$

$$I(t) \equiv I_0\left[1 + m_I e^{j\omega_0 t}\right]$$

Laser Direct Modulation

Laser Transfer Function – Small Signal Analysis

$$I = I_0 + \Delta I$$

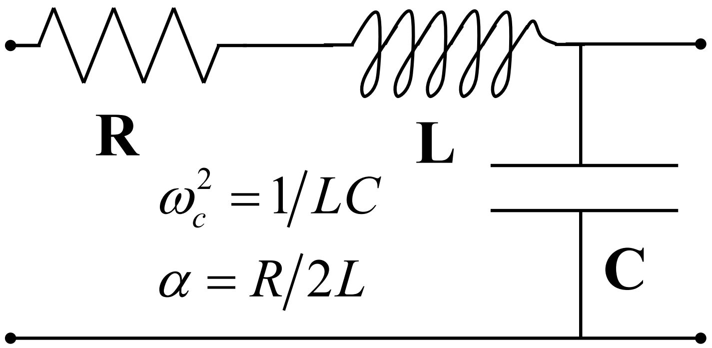
$$P = P_0 + \Delta P$$

$$H(\omega_0) \equiv \frac{\Delta P}{\Delta I} = \frac{P_0 \dfrac{I_0}{I_0 - I_{th}} m_I M(\omega_0) e^{j\omega_0 t}}{I_0 m_I e^{j\omega_0 t}} = \frac{1-R}{2\sqrt{R}} \frac{1}{\alpha_t L} \frac{hf}{q} M(\omega_0)$$

$$P_0 = \frac{1-R}{2\sqrt{R}} \frac{1}{\alpha_t L} \frac{hf}{q} (I_0 - I_{th})$$

$$\frac{H(\omega_0)}{H(0)} = M(\omega_0) = \frac{\omega_c^2}{\omega_c^2 - \omega_0^2 + j2\alpha\omega_0}$$

2nd order low-pass RLC filter



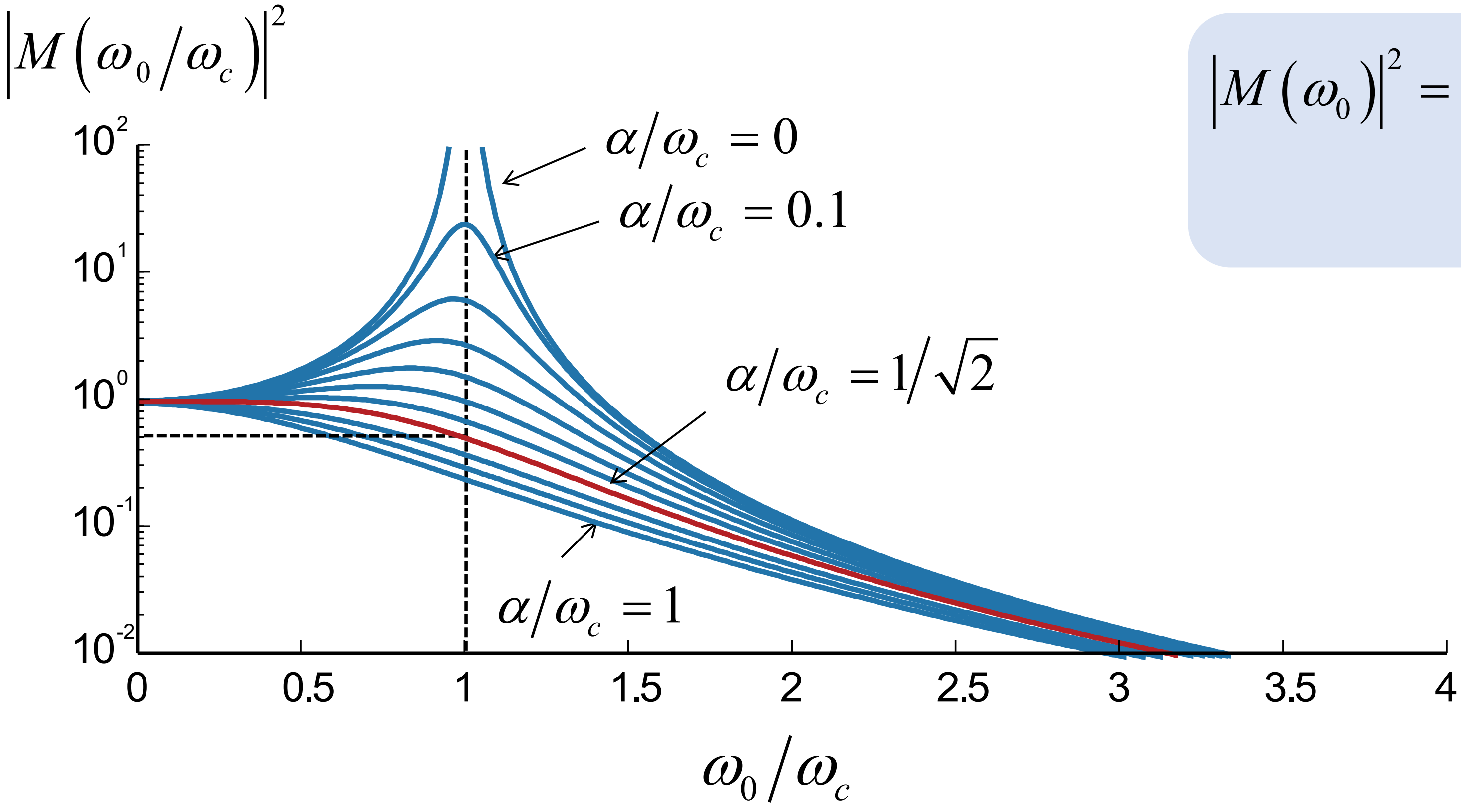
$$\omega_c^2 = 1/LC$$

$$\alpha = R/2L$$

$$\boxed{\left|M(\omega_0)\right|^2 = \frac{1}{\left(1 - \dfrac{\omega_0^2}{\omega_c^2}\right)^2 + \left(\dfrac{2\alpha}{\omega_c^2}\omega_0\right)^2}}$$

Laser Direct Modulation

Laser Transfer Function – Small Signal Analysis



$$\left|M\left(\omega_0\right)\right|^2 = \frac{1}{\left(1-\frac{\omega_0^2}{\omega_c^2}\right)^2 + \left(\frac{2\alpha}{\omega_c^2}\omega_0\right)^2}$$

$$2\alpha = \frac{1}{\tau_r} + \tau_p \omega_c^2$$

$$\omega_c^2 = \frac{v\Gamma a}{qV}\left(I_0 - I_{th}\right)$$

Trade-off ➡

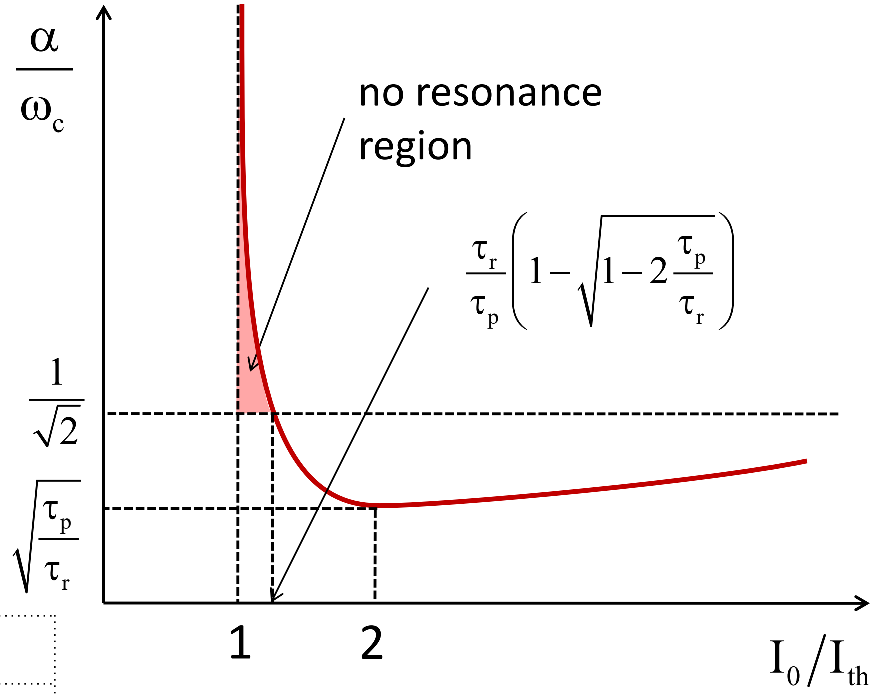
$\alpha/\omega_c < 1/\sqrt{2} \rightarrow$ resonance

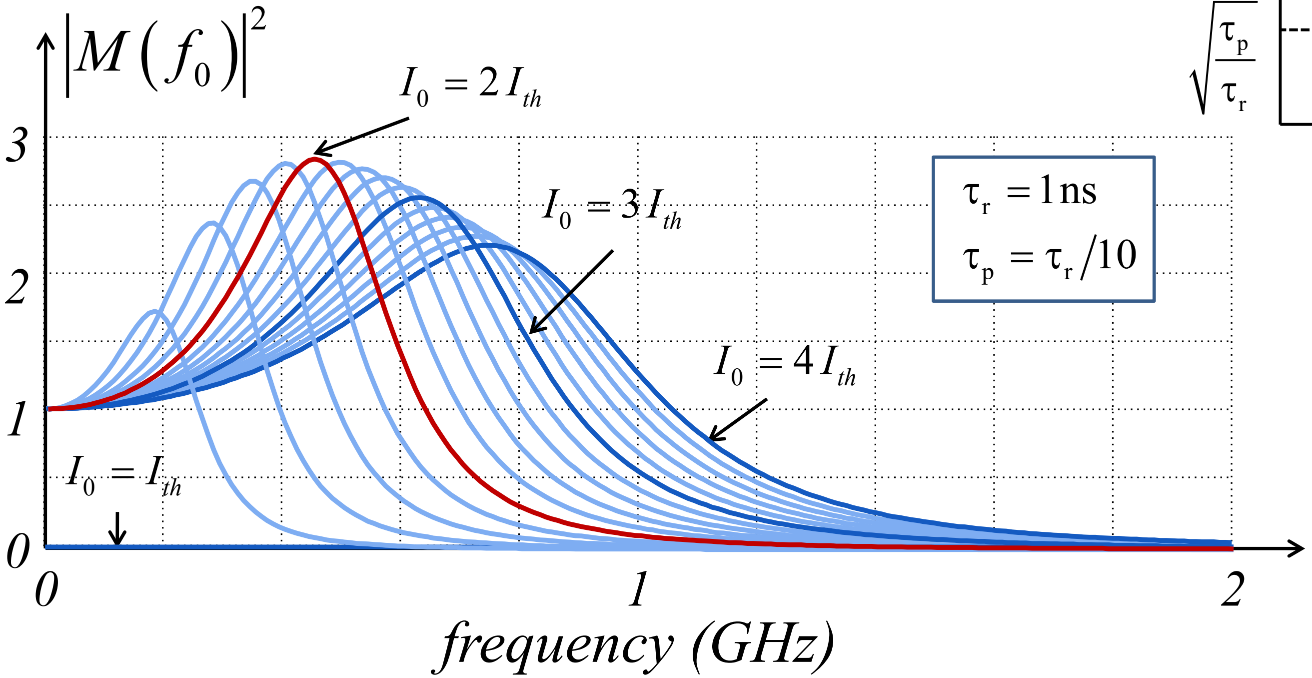
$\alpha/\omega_c > 1/\sqrt{2} \rightarrow$ bandwidth ↓↓

Laser Direct Modulation

Laser Transfer Function – Small Signal Analysis

$$N_0 = 0 \Rightarrow \begin{cases} \alpha = \dfrac{1}{2\tau_r}\left(\dfrac{I_0}{I_{th}}\right) \\ \omega_c^2 = \dfrac{1}{\tau_r\tau_p}\left(\dfrac{I_0}{I_{th}} - 1\right) \end{cases} \Rightarrow$$

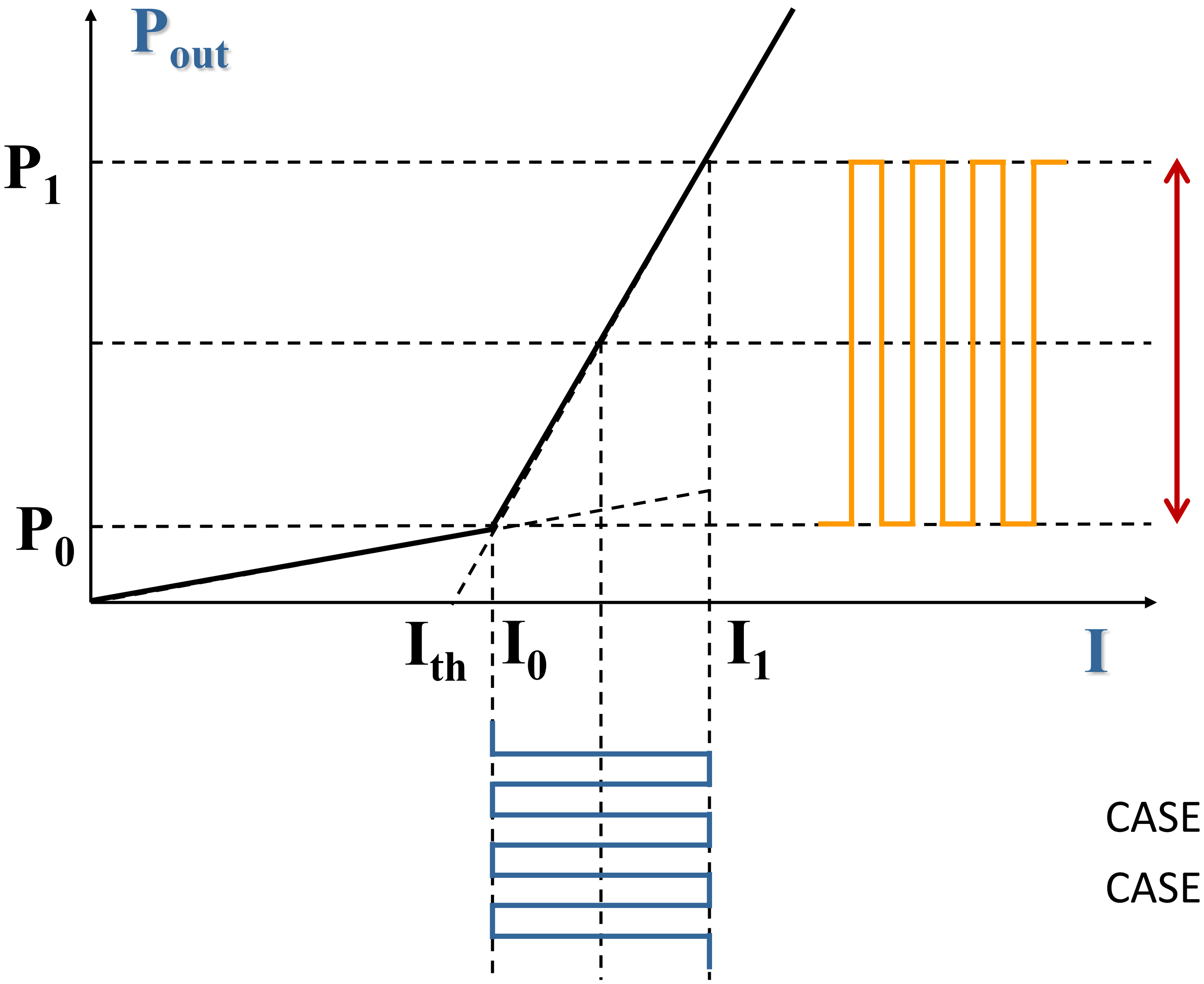




$$\tau_p \uparrow \;\rightarrow\; \omega_c \downarrow$$

Laser Direct Modulation

Digital Modulation



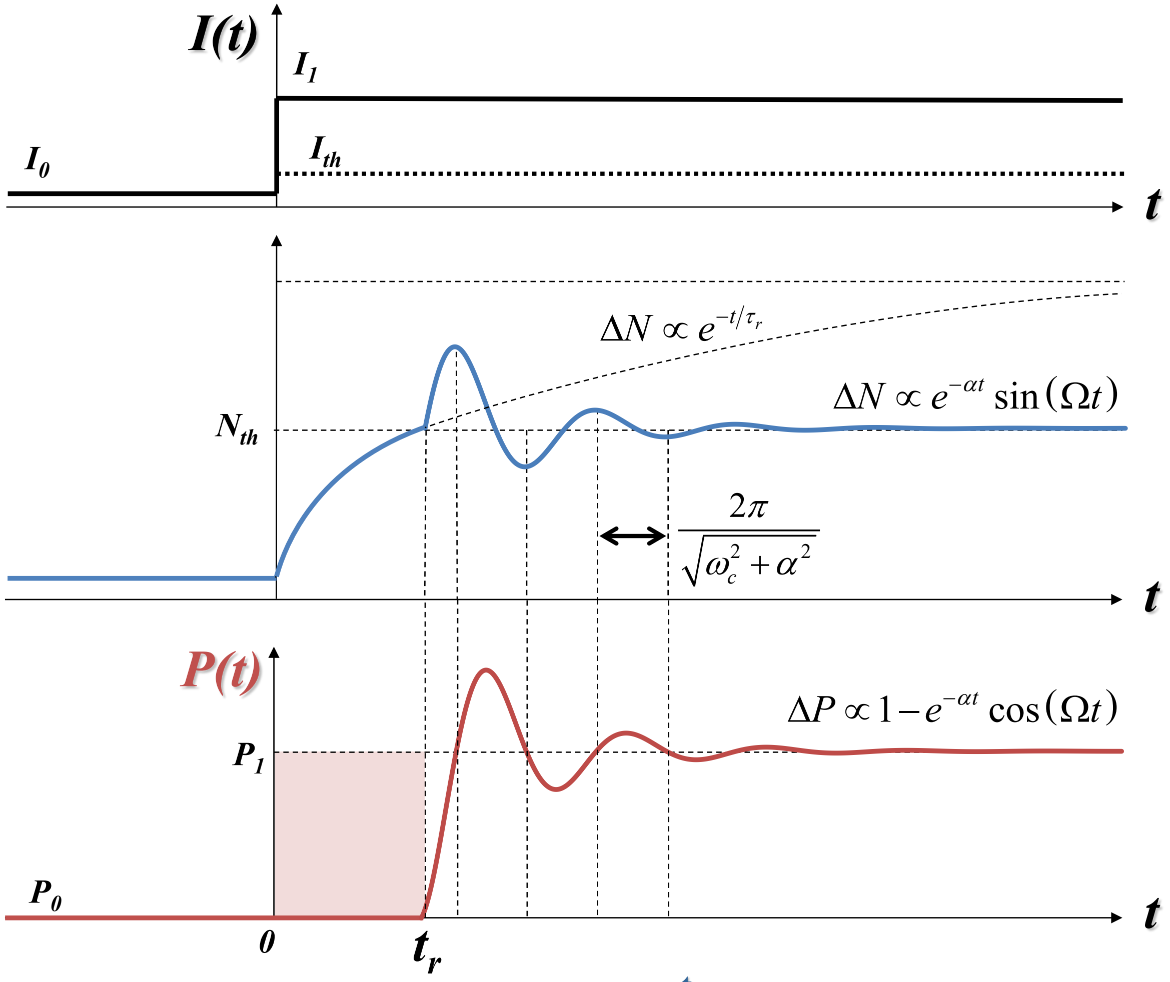
$$\frac{\partial N}{\partial t} = \frac{I}{qV} - \frac{N}{\tau_r} - v \cdot gS$$

$$\frac{\partial S}{\partial t} = v \cdot gS - v \cdot \alpha_t S$$

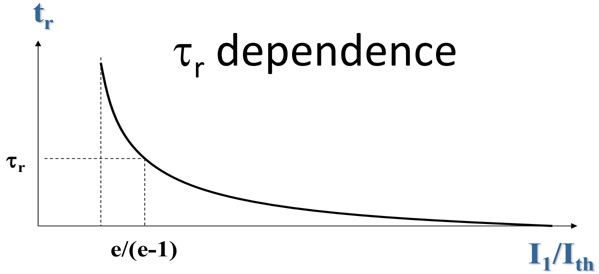
CASE 1 → $I_0 < I_{th} < I_1$

CASE 2 → $I_{th} < I_0 < I_1$

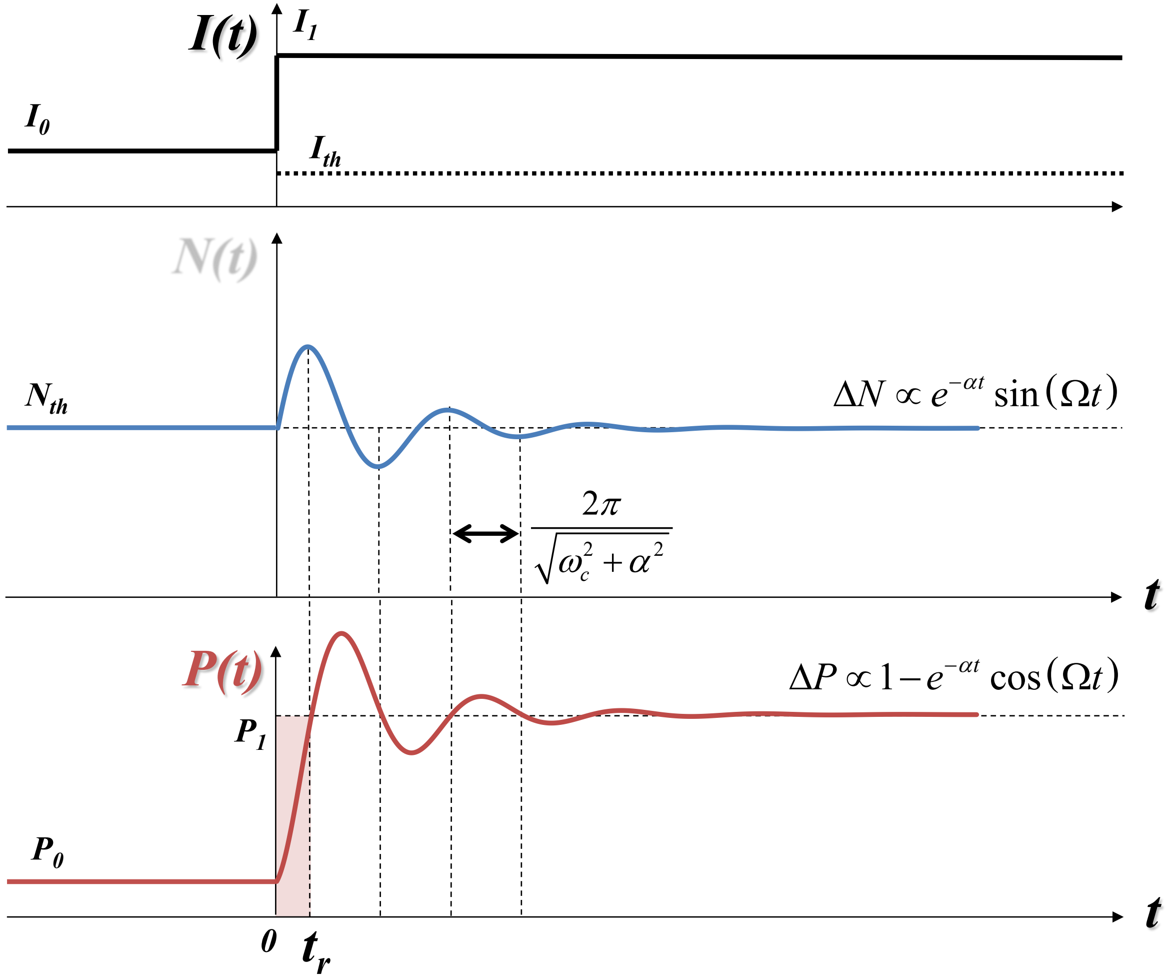
Laser Direct Modulation



$$t_r = \tau_r \ln\frac{I_1-I_0}{I_1-I_{th}} \xrightarrow{I_0=0} \tau_r \ln\frac{I_1/I_{th}}{I_1/I_{th}-1}$$



Laser Direct Modulation



$$t_r \approx \left[\frac{2qV}{v\Gamma a}\frac{\ln\left(\left(I_1-I_{th}\right)/\left(I_0-I_{th}\right)\right)}{I_1-I_0}\right]^{1/2}$$

No τ_r dependence

The response time in this case is much faster.

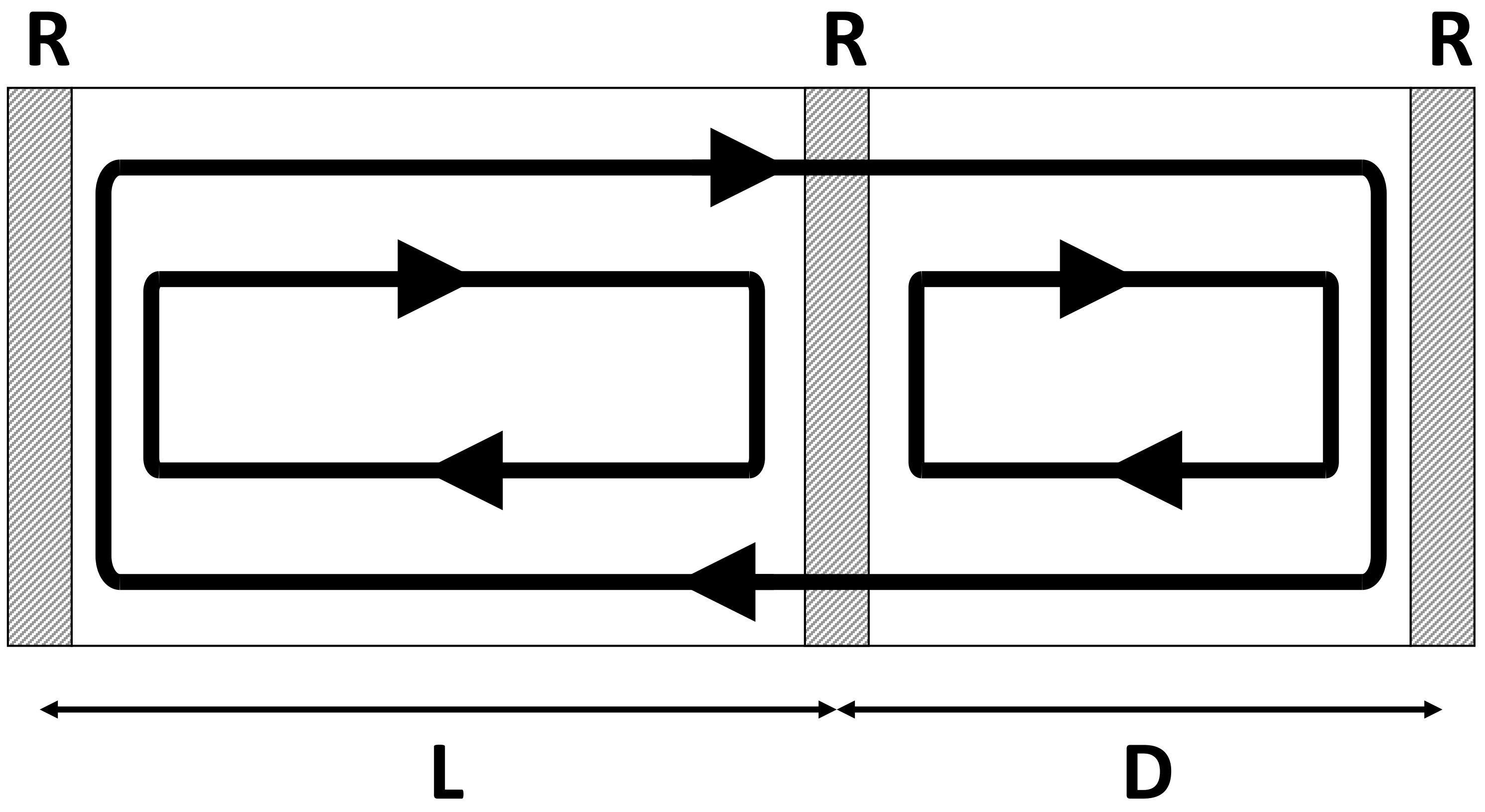
$I_1 - I_0 = \alpha \cdot I_{th} \;\rightarrow\; I_1 \uparrow \rightarrow t_r \downarrow$

Advanced Laser Structures

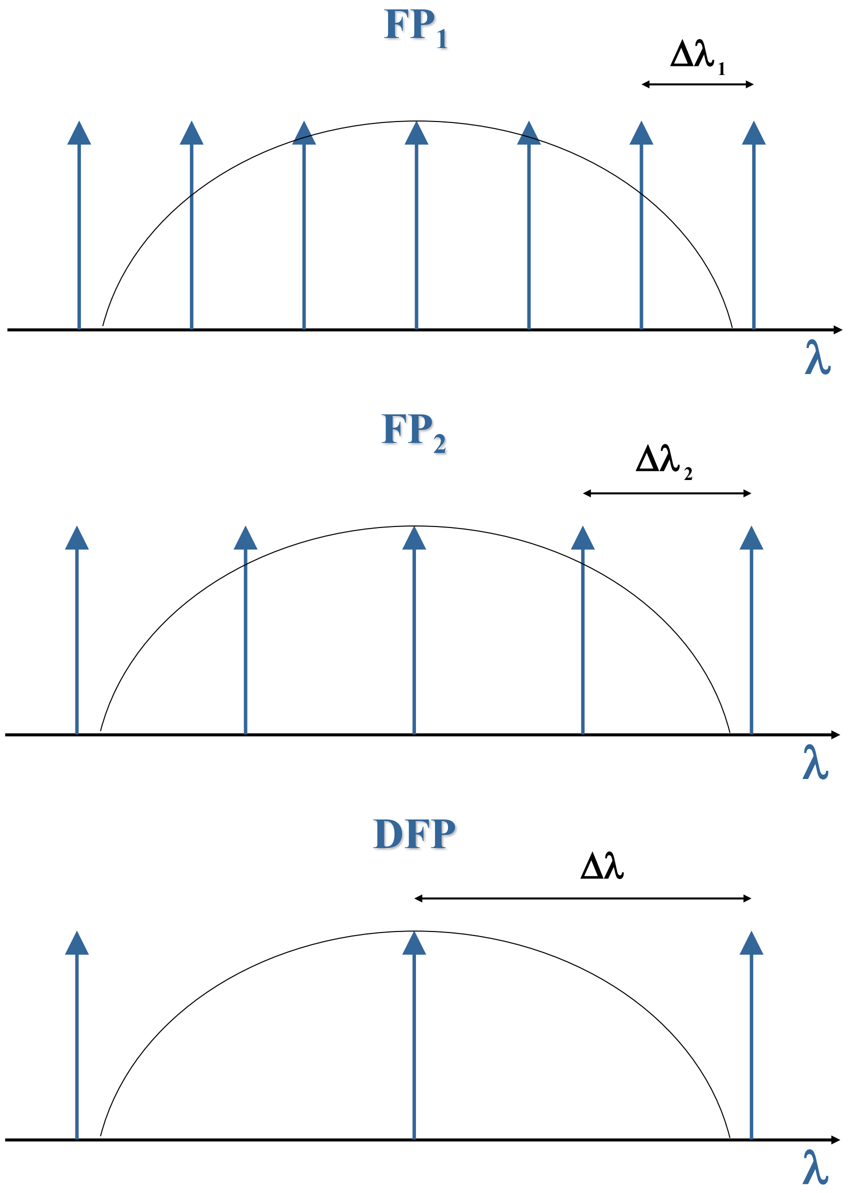
MODERN LASER STRUCTURES

Coupled Cavities

COUPLED FABRY-PEROT CAVITIES



Advanced Laser Structures



$$\Delta\lambda_1 = \frac{\lambda^2}{2Ln_1}$$

$$\Delta\lambda_2 = \frac{\lambda^2}{2Dn_2}$$

$$\Delta\lambda = \frac{\lambda^2}{2\left|Dn_2 - Ln_1\right|} = \frac{\lambda^2}{2n\left|D - L\right|}$$

$$n_2 = n_1 = n$$

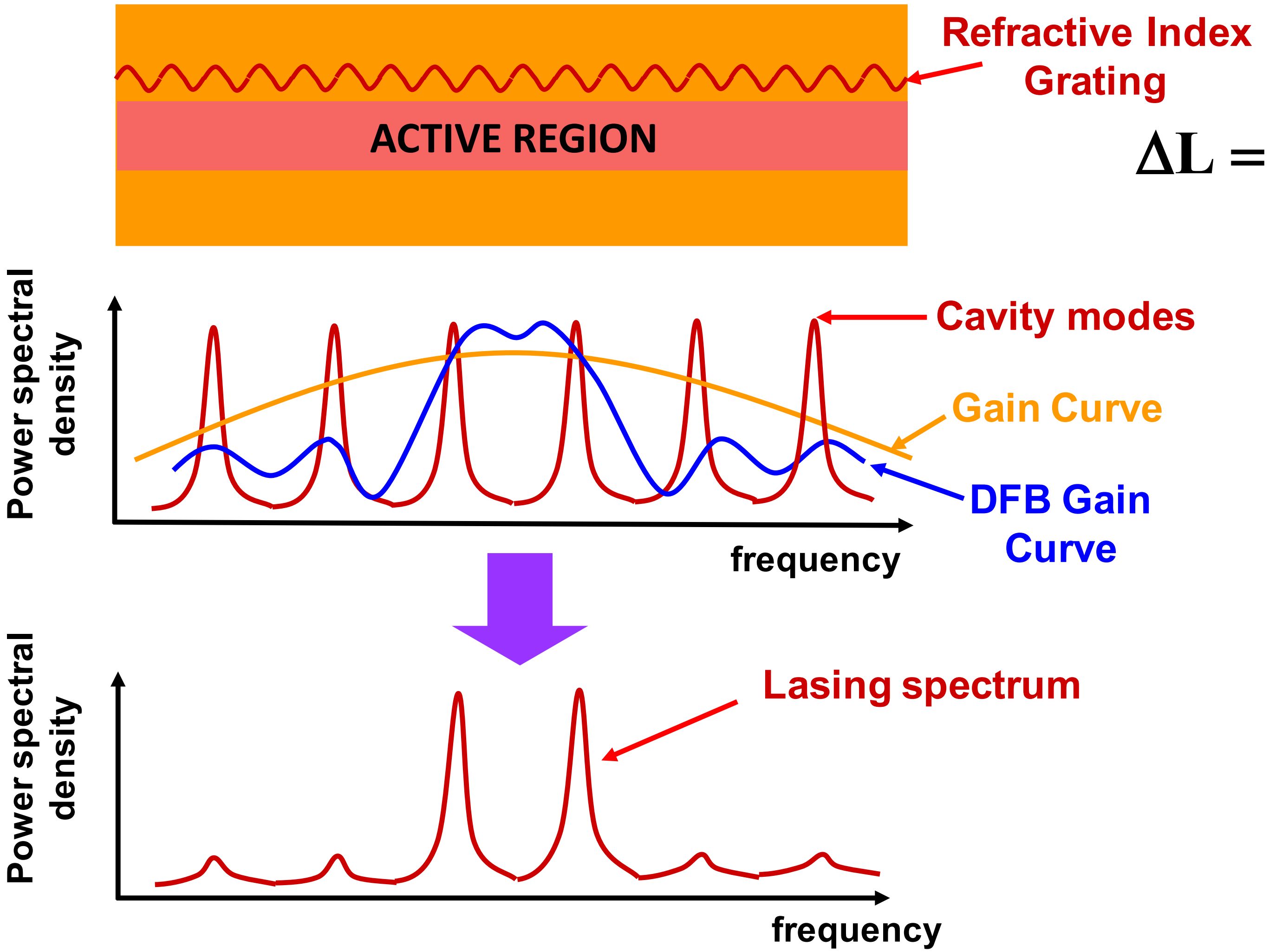
$$\partial\lambda \approx 30\text{MHz}$$

tunning ~ 5 nm

speed ~ 1 µs

Advanced Laser Structures

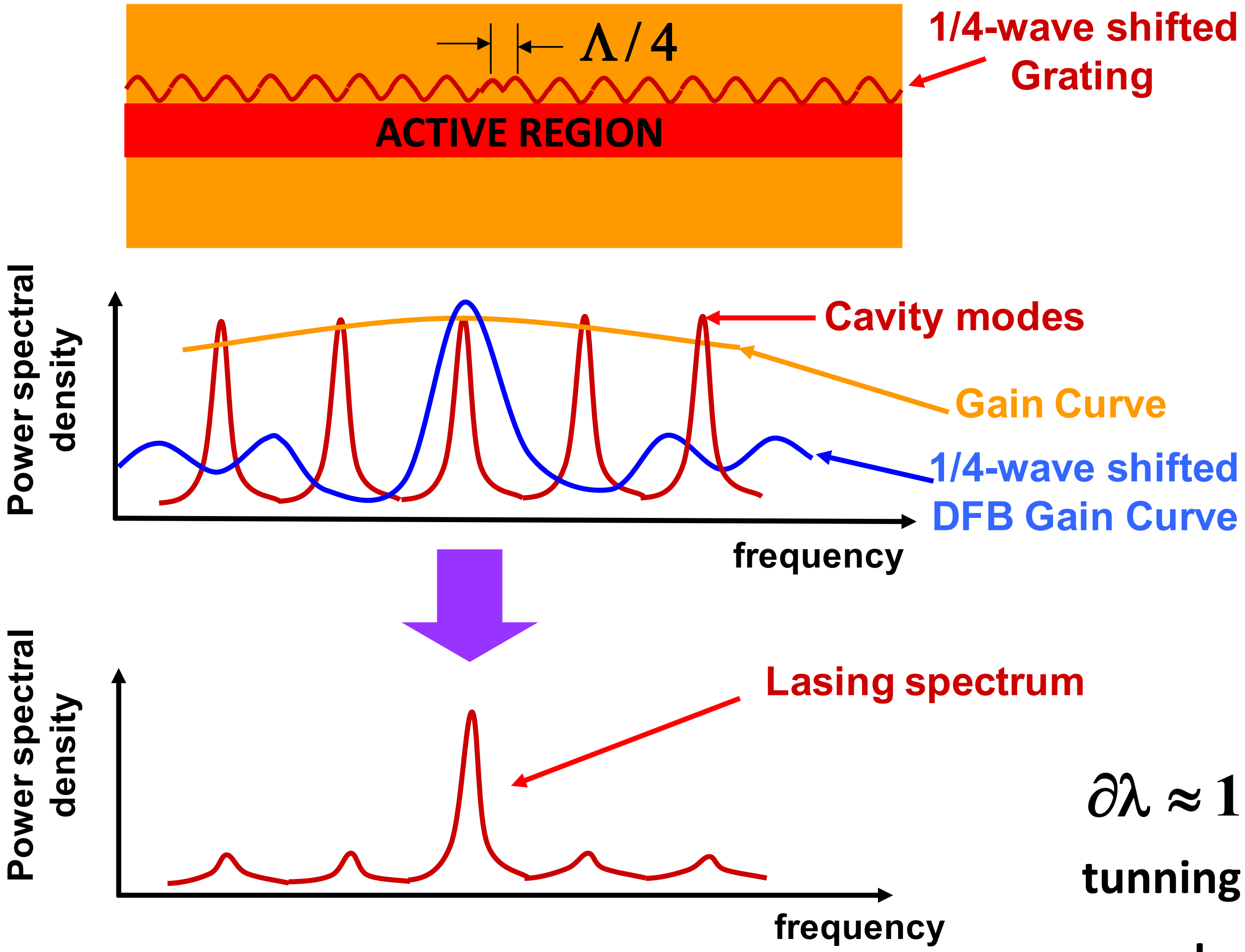
Distributed Feed-Back (DFB) Lasers



$$\Delta L = m\frac{\lambda}{2n}$$

Advanced Laser Structures

Distributed Feed-Back (DFB) Lasers



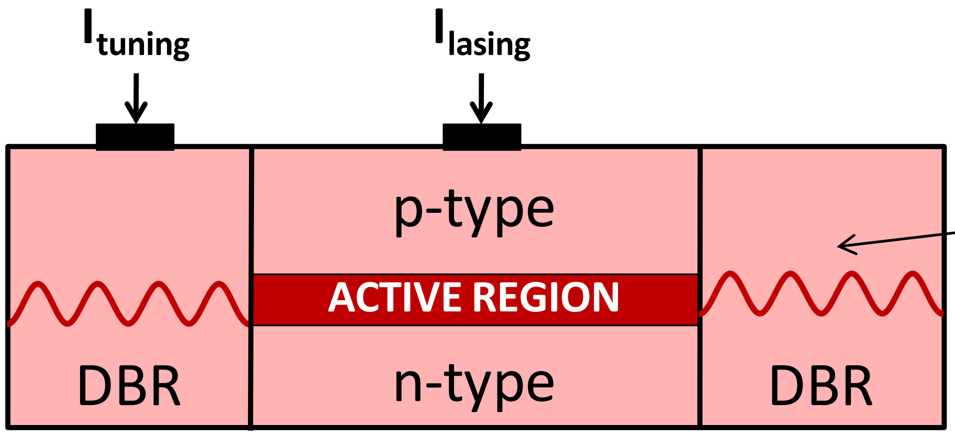
$$\partial\lambda \approx 10\text{MHz}$$

tunning ~ 5 nm

speed ~ 1 μs

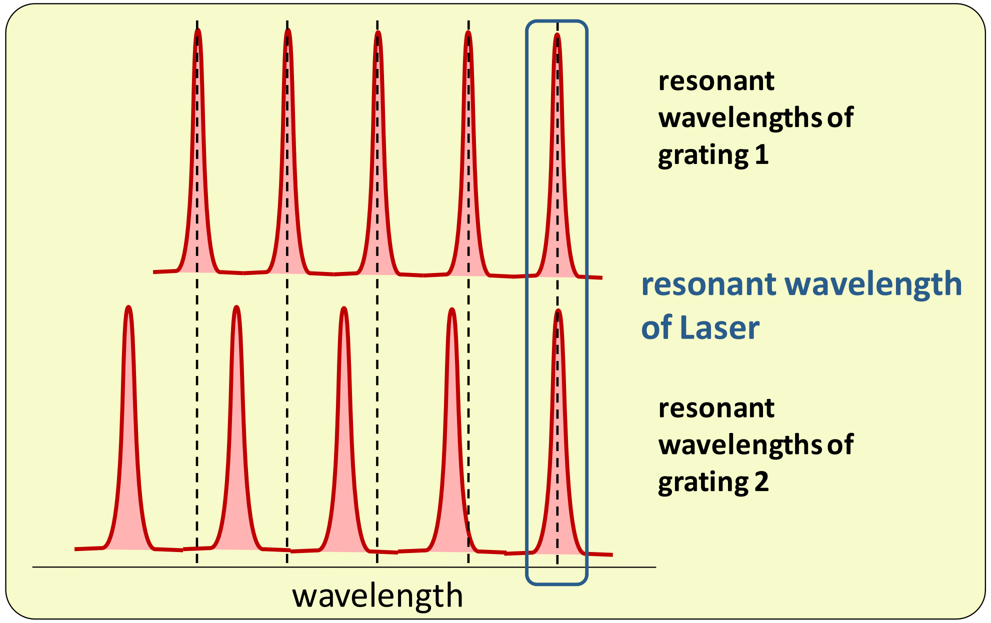
Advanced Laser Structures

Distributed Bragg Reflector (DBR) Lasers



wavelength dependent mirrors

$$\Delta L = m\frac{\lambda}{2n}$$



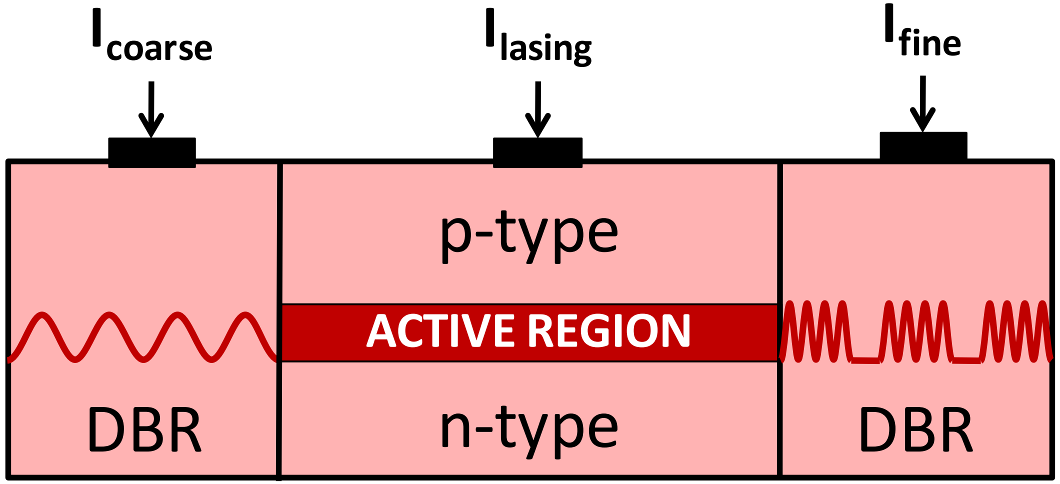
$$\partial\lambda \approx 30\text{MHz}$$

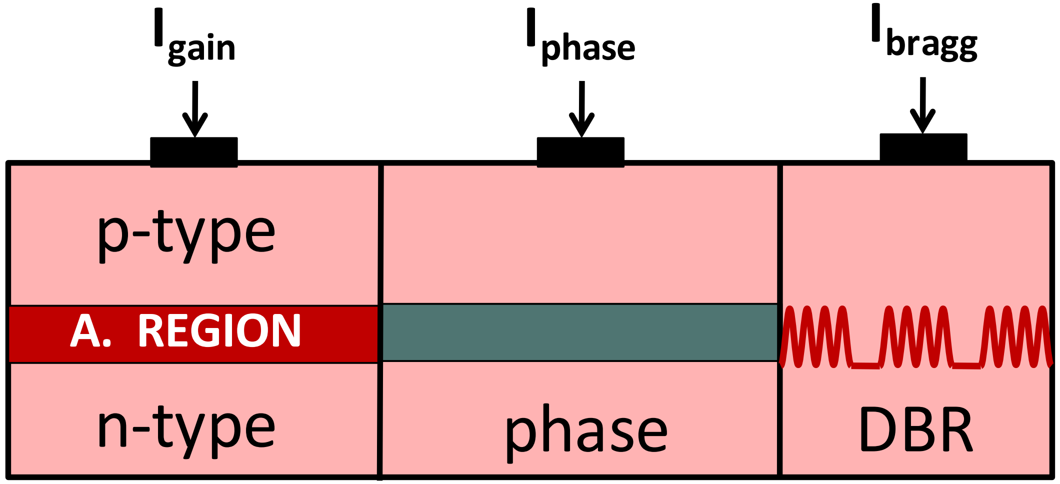
tunning ~ 15 nm

speed ~ 10 ns

Advanced Laser Structures

Sampled Grating DBR (SG-DBR) Lasers – 3 sections





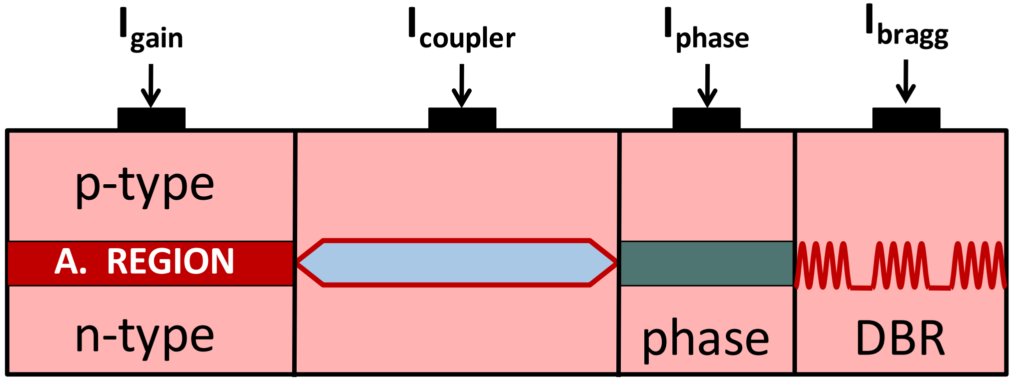
$\partial\lambda \approx 10\text{MHz}$

tunning ~ 30 nm

speed ~ 0.1 ns

Advanced Laser Structures

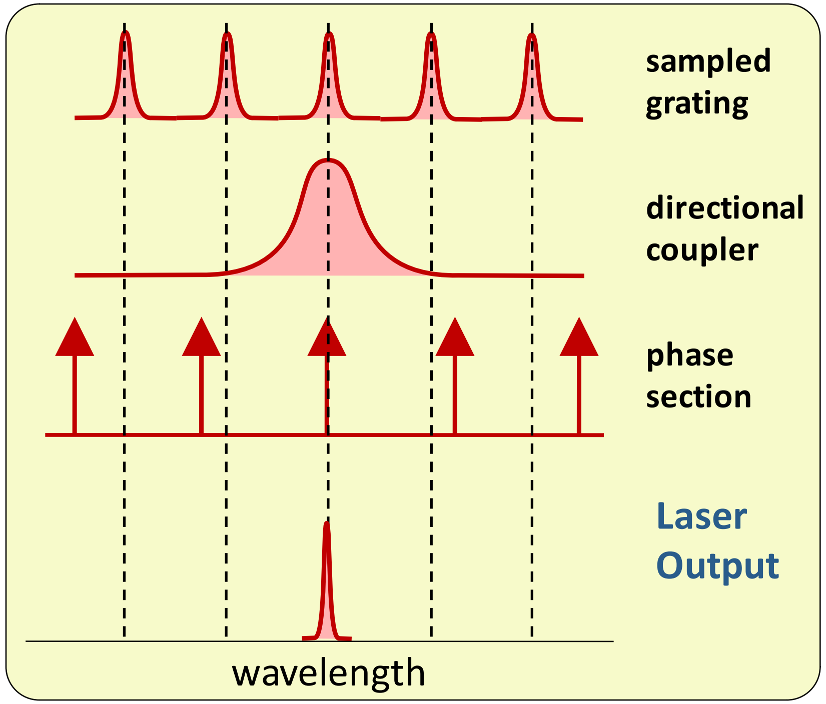
Grating Coupler Sampled Reflector (GCSR) Lasers – 4 sections

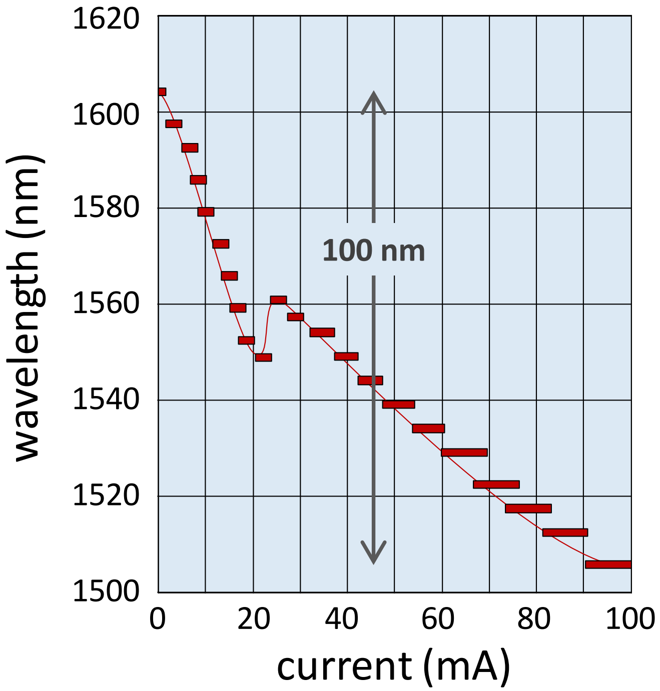


$\partial\lambda \approx 1$ MHz

tunning ~ 100 nm

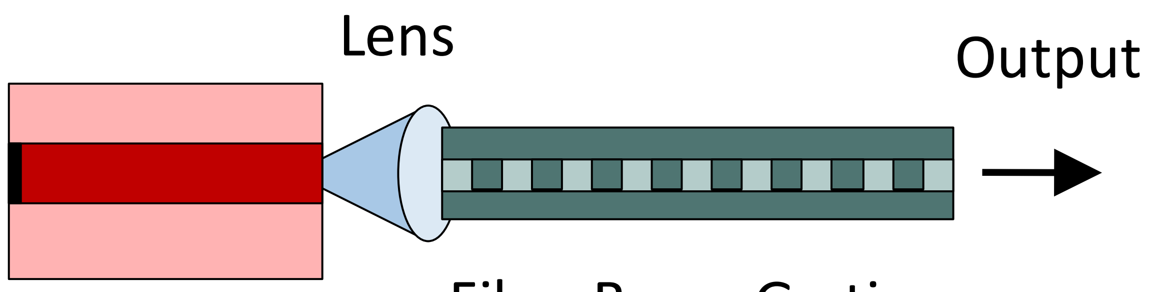
speed ~ 0.1 ns





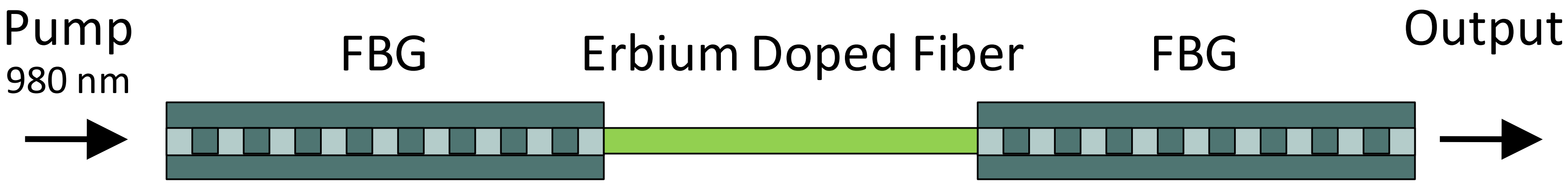
Advanced Laser Structures

External Cavity Lasers



$\partial\lambda \approx 50\text{KHz}$

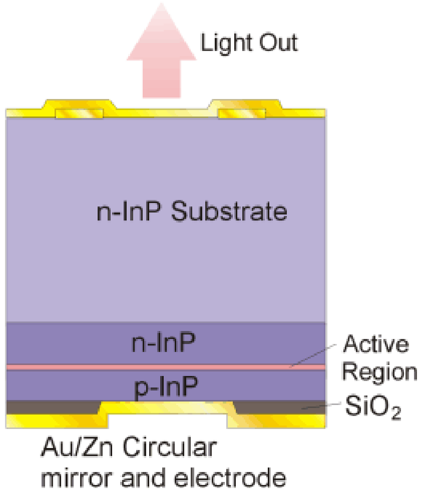
Fiber Lasers (non semi-conductor)



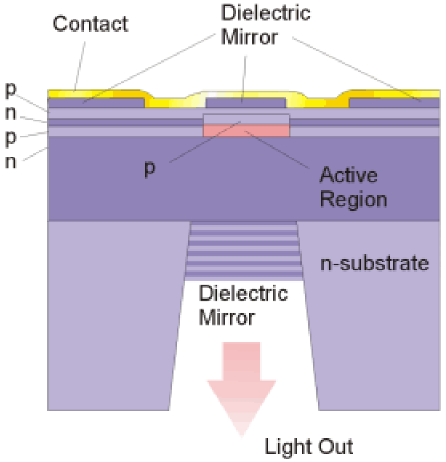
Output Power ~10 W

Advanced Laser Structures

Vertical Cavity Surface Emitting Lasers (VCSELs)

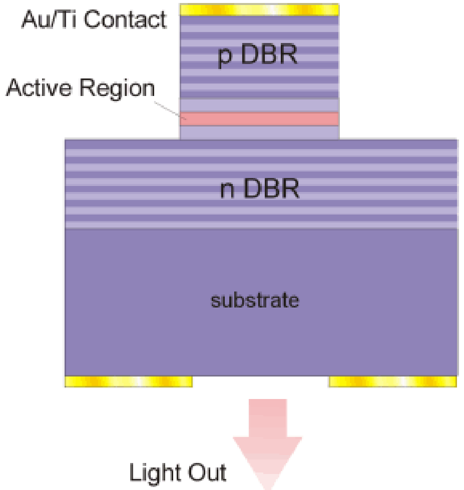


(a) metallic reflector VCSEL

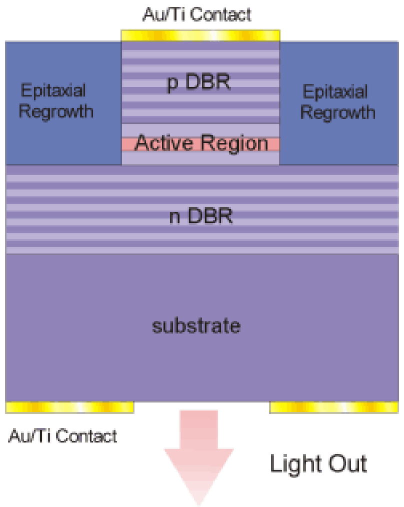


(b) etched well VCSEL

Cheap singlemode Lasers @ 1^{st} , 2^{nd} , and 3^{rd} window



(c) air post VCSEL



(d) burned regrouwth VCSEL